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(54) **LOW-DOSE RADIOGRAPHIC IMAGING SYSTEM**

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See application file for complete search history.

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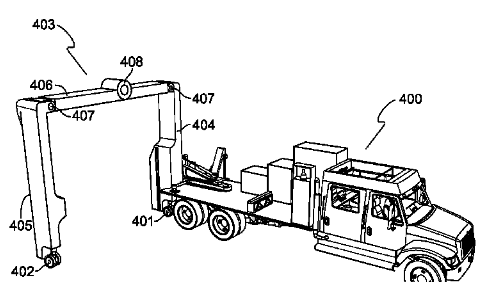
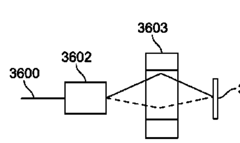
(57) **ABSTRACT**

An inspection system for scanning cargo and vehicles is described which employs an X-ray source that includes an electron beam generator, for generating an electron beam; an accelerator for accelerating said electron beam in a first direction; and, a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements, wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that the target substantially only generates X-rays focused toward a high density section in the scanned object, which is estimated in a second pulse using image data captured by a detector array in a first pulse. The electron beam direction is optimized by said X-ray source during said second pulse to focus X-rays towards said high density section based on said image data in said first pulse.

45 Claims, 29 Drawing Sheets





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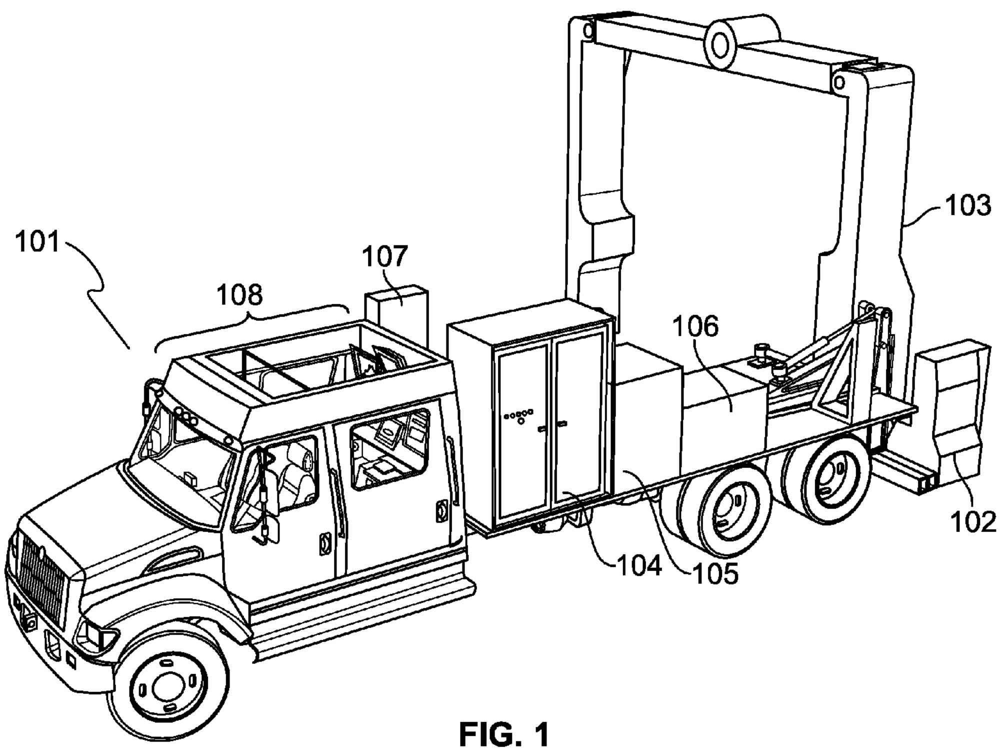


FIG. 1

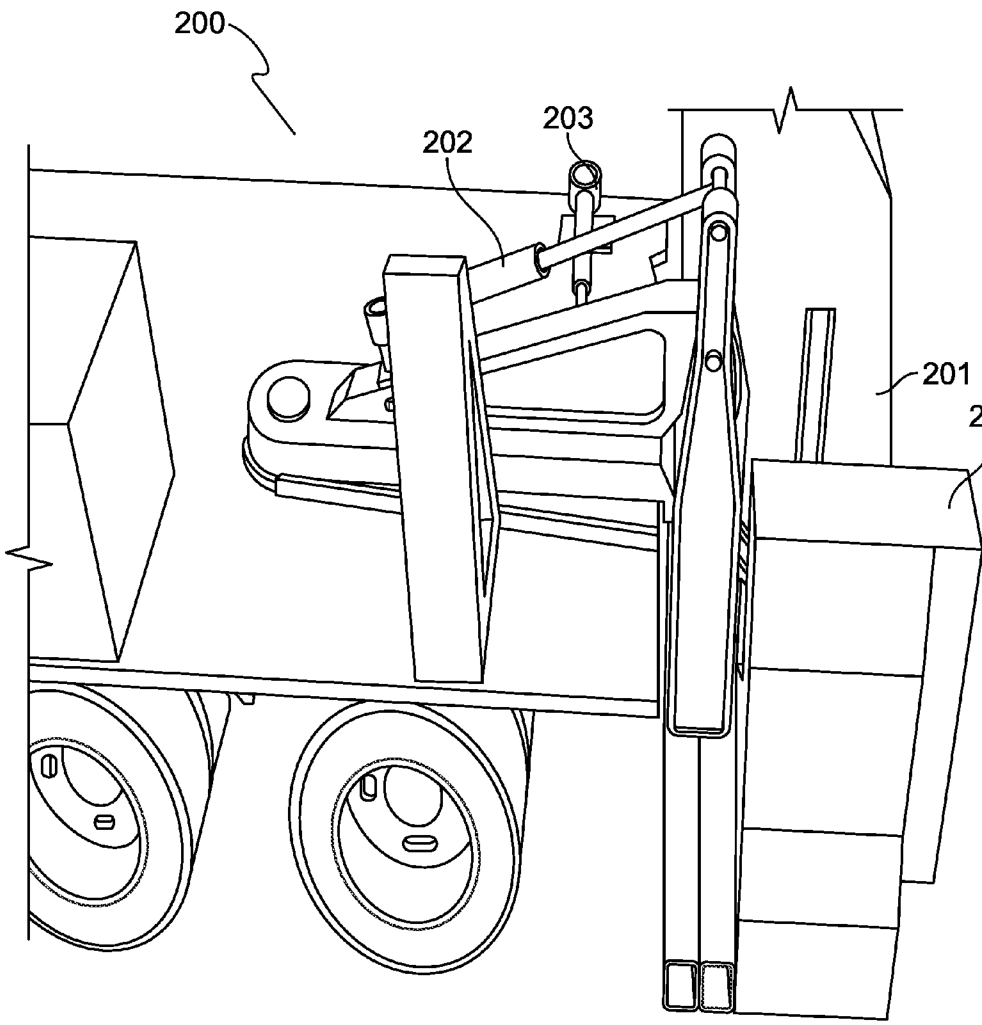


FIG. 2

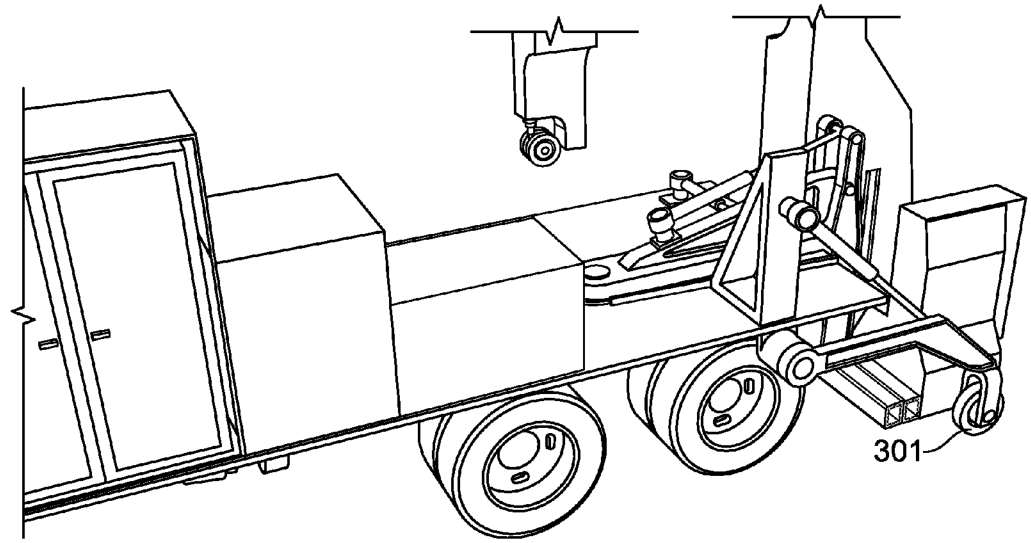


FIG. 3

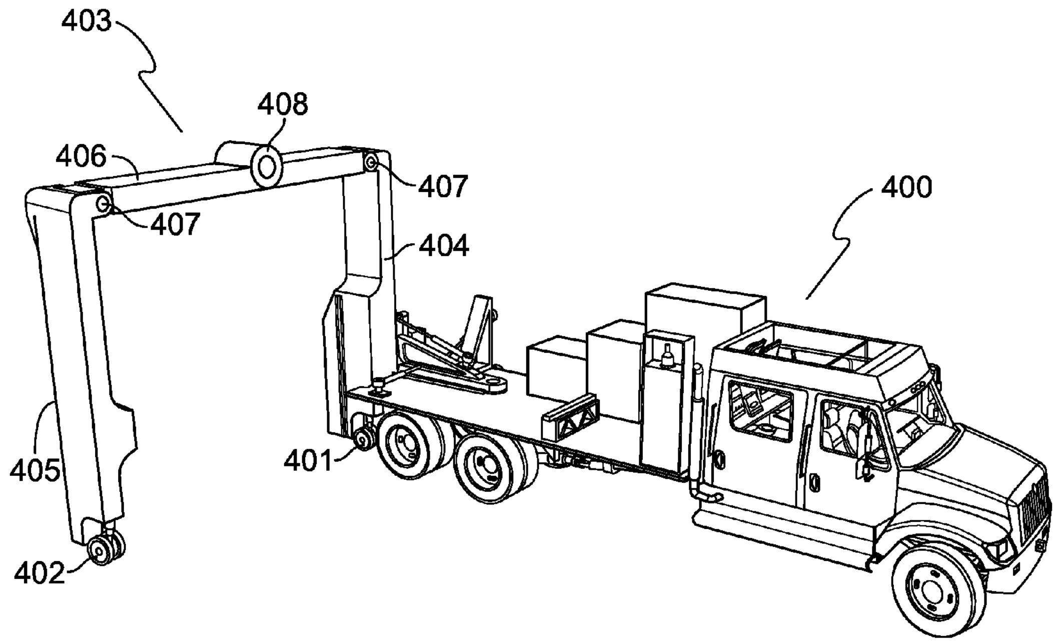


FIG. 4

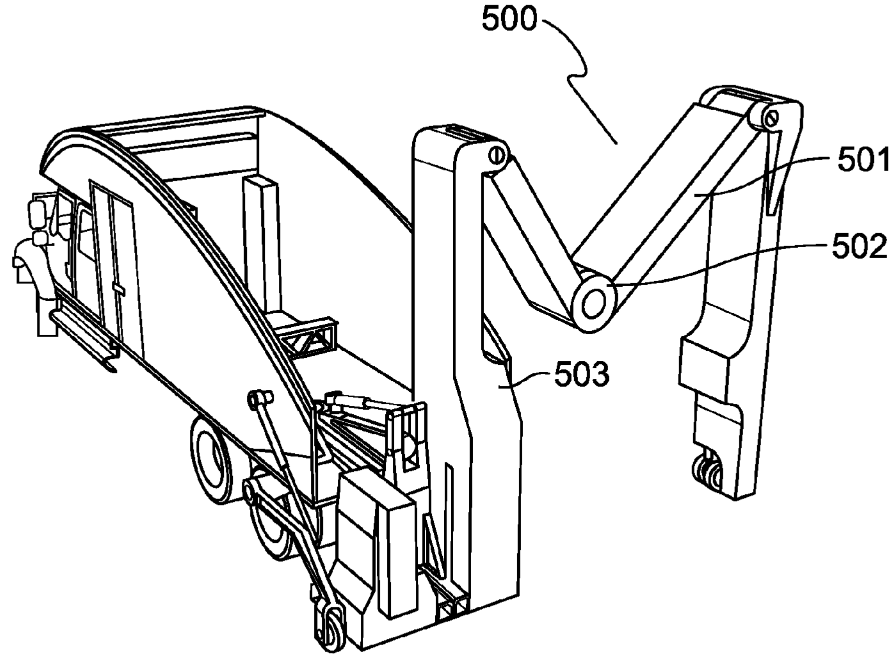


FIG. 5a

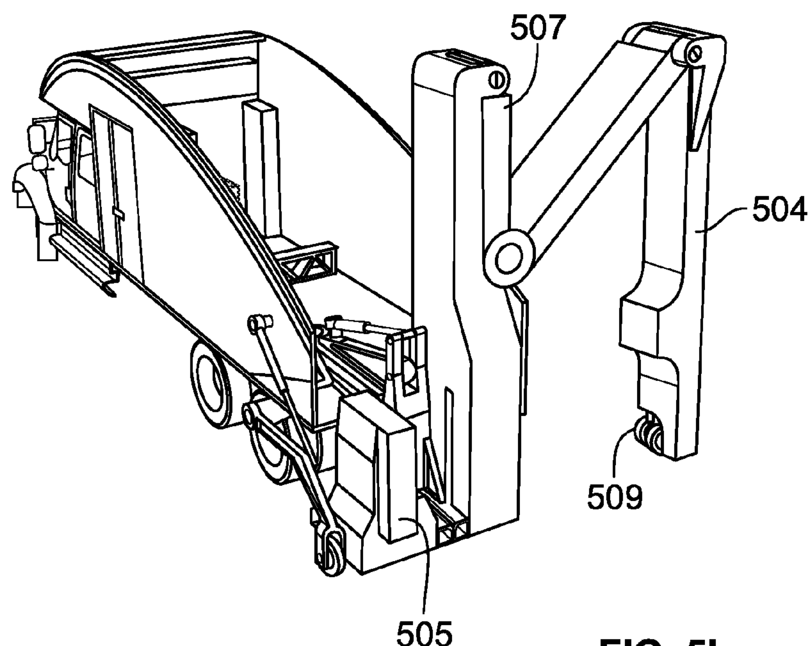


FIG. 5b

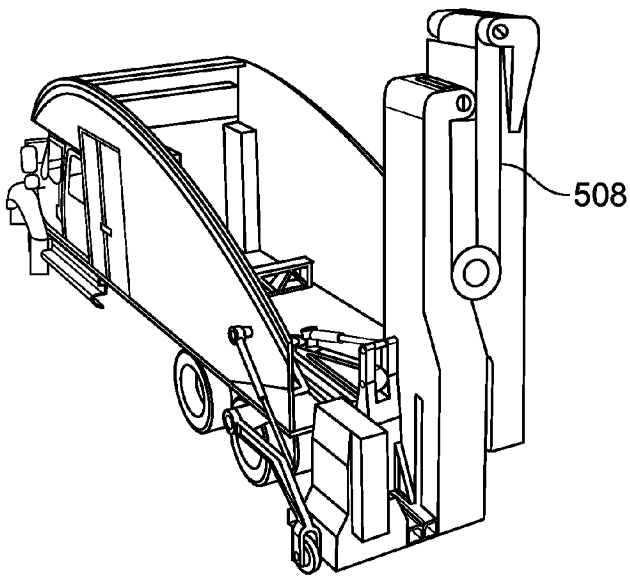


FIG. 5c

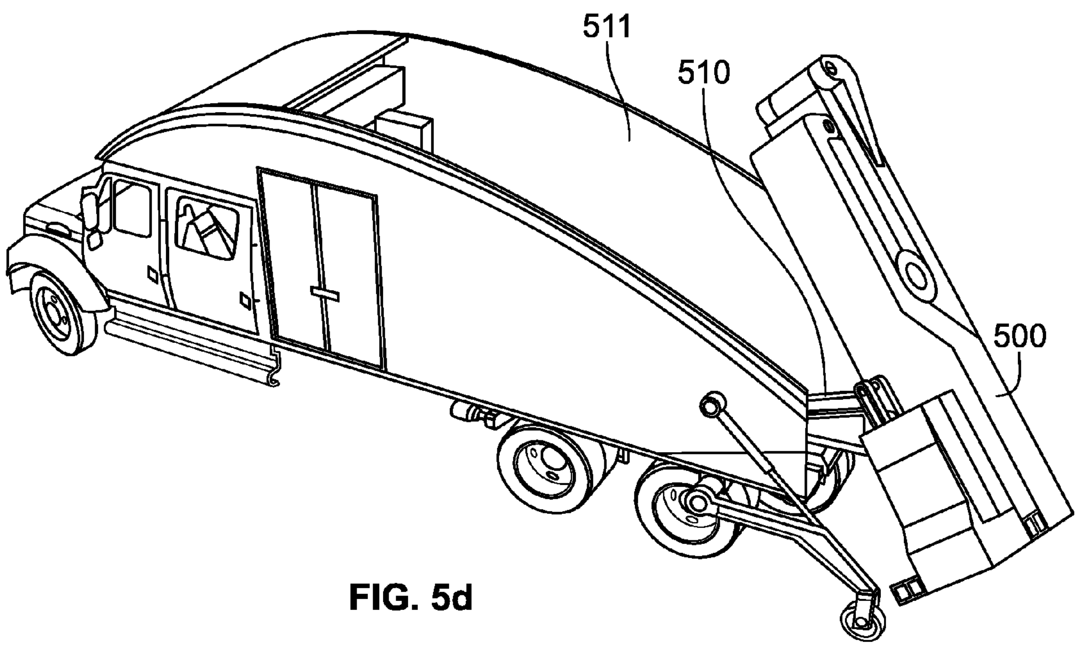


FIG. 5d

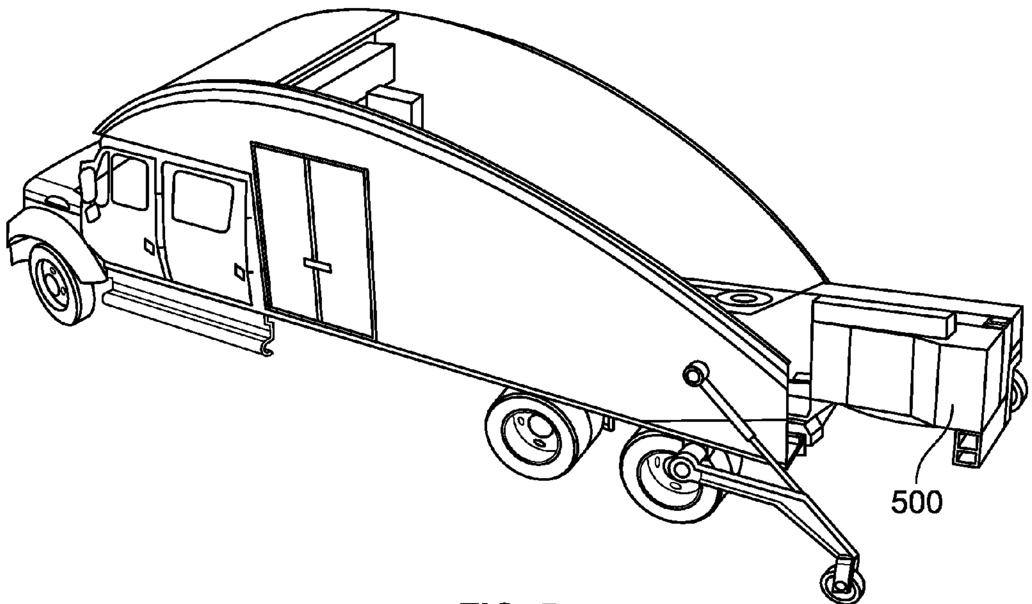


FIG. 5e

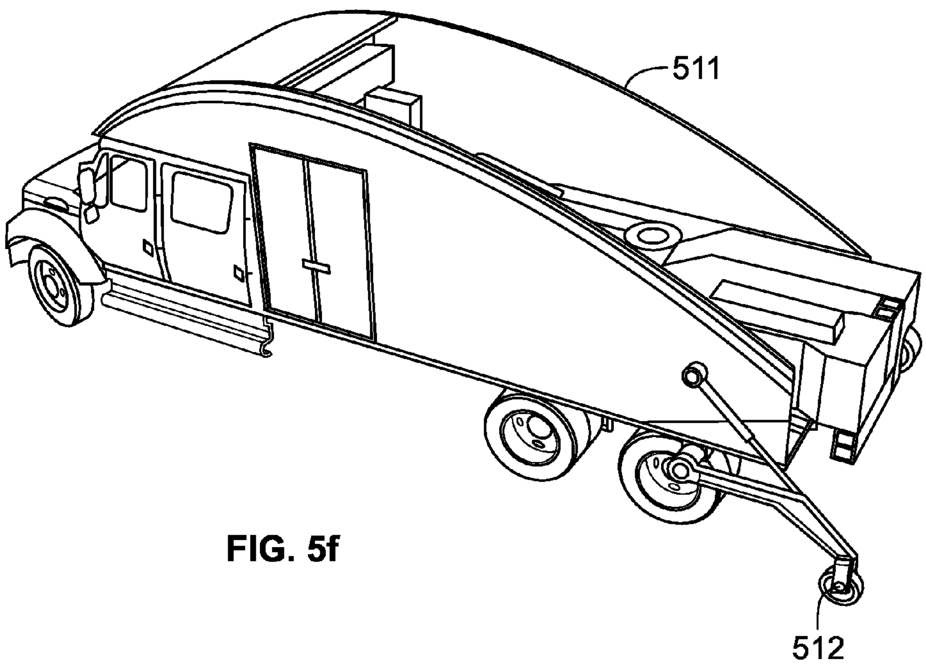


FIG. 5f

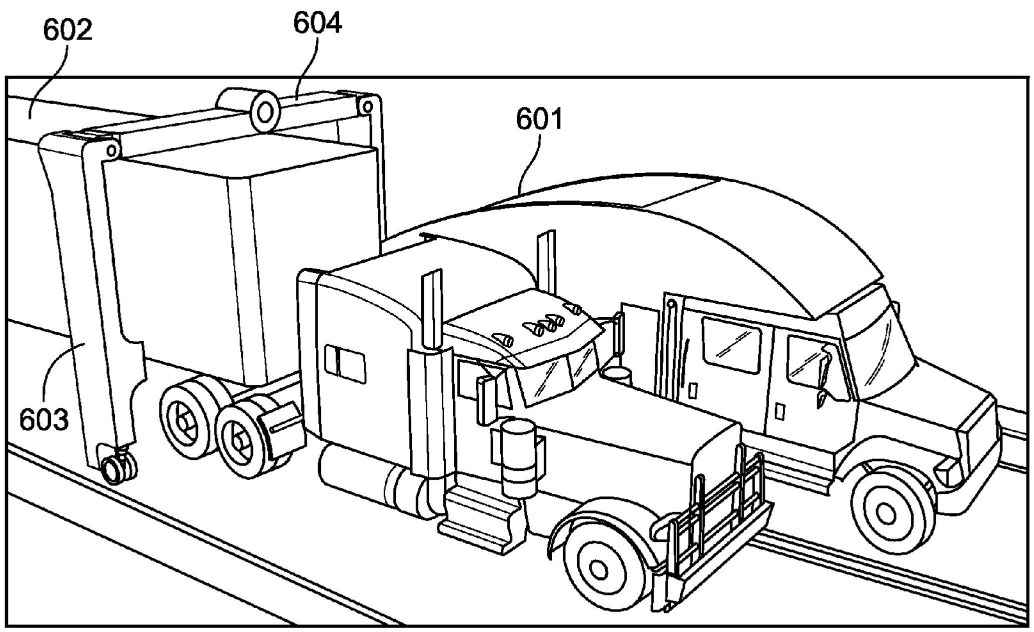


FIG. 6

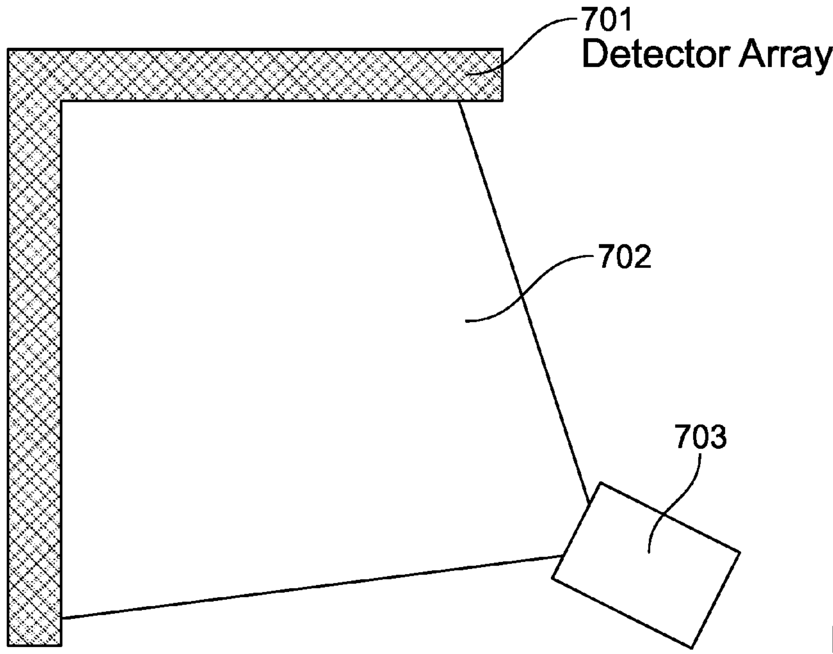


FIG. 7

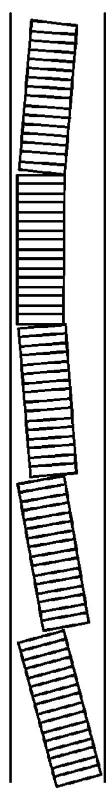


FIG. 8

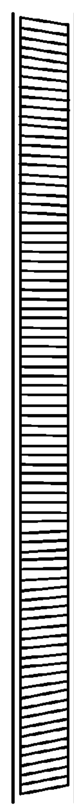


FIG. 9

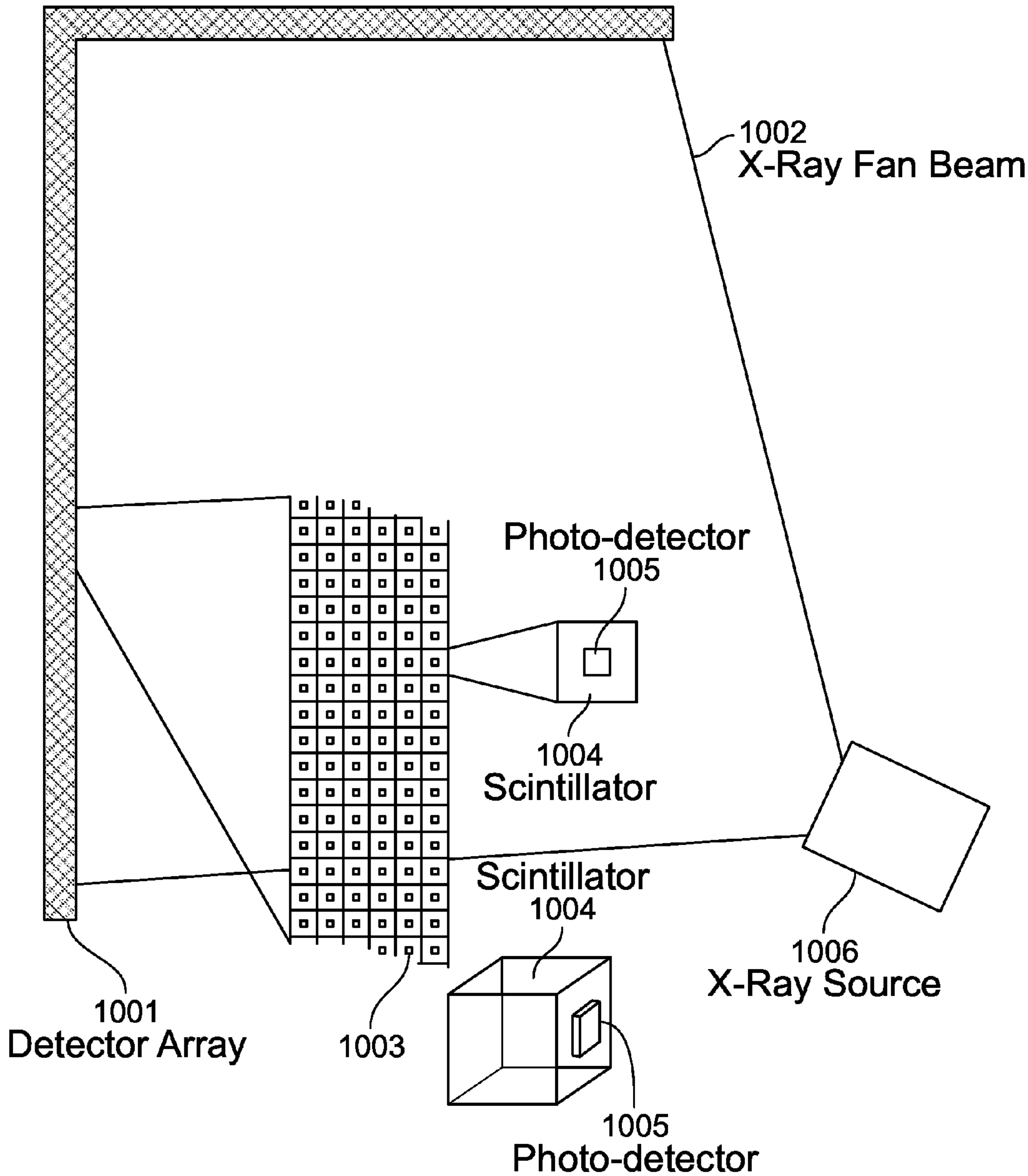

1002
X-Ray Fan Beam
Photo-detector
1005
1004
Scintillator
Scintillator
1004
1006
X-Ray Source
1001
Detector Array
1003
1005
Photo-detector

FIG. 10

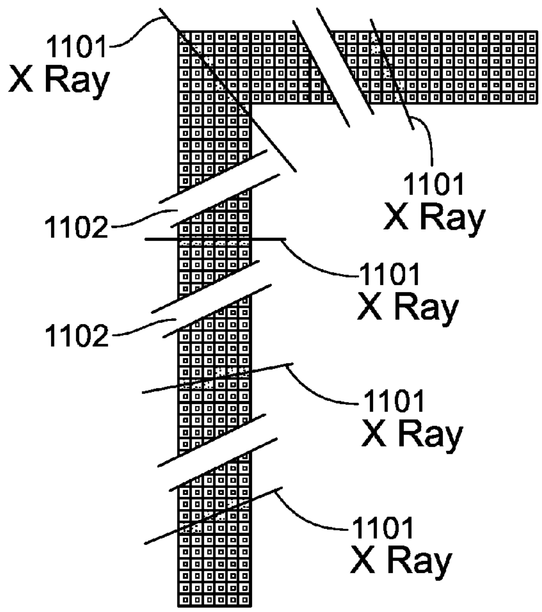

1101
X Ray
1101
X Ray
1102
1101
X Ray
1102
1101
X Ray
1101
X Ray

FIG. 11

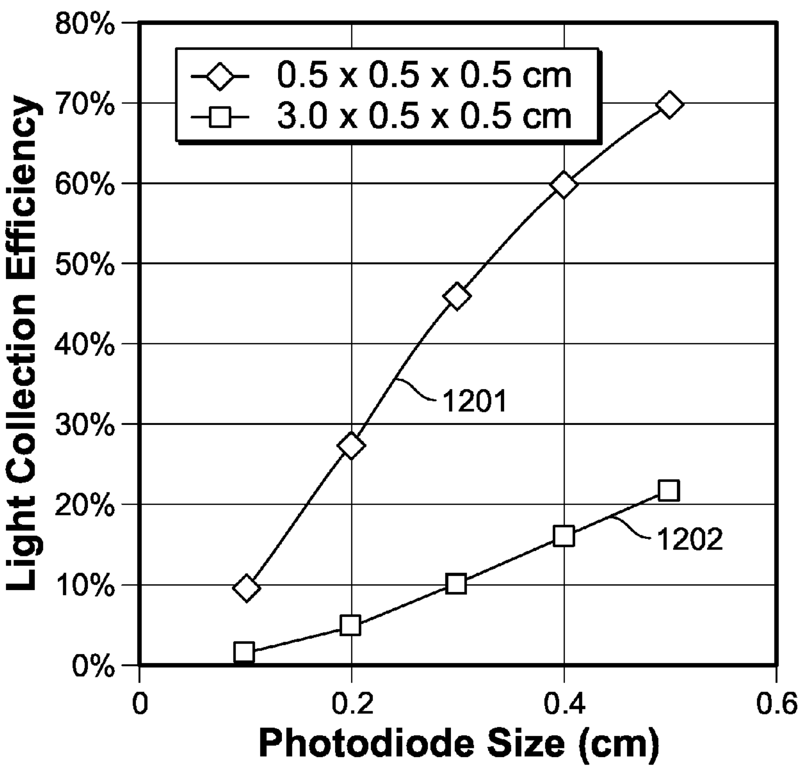

0.5 x 0.5 x 0.5 cm
3.0 x 0.5 x 0.5 cm
Light Collection Efficiency
80%
70%
60%
50%
40%
30%
20%
10%
0%
1201
1202
0
0.2
0.4
0.6
Photodiode Size (cm)

FIG. 12

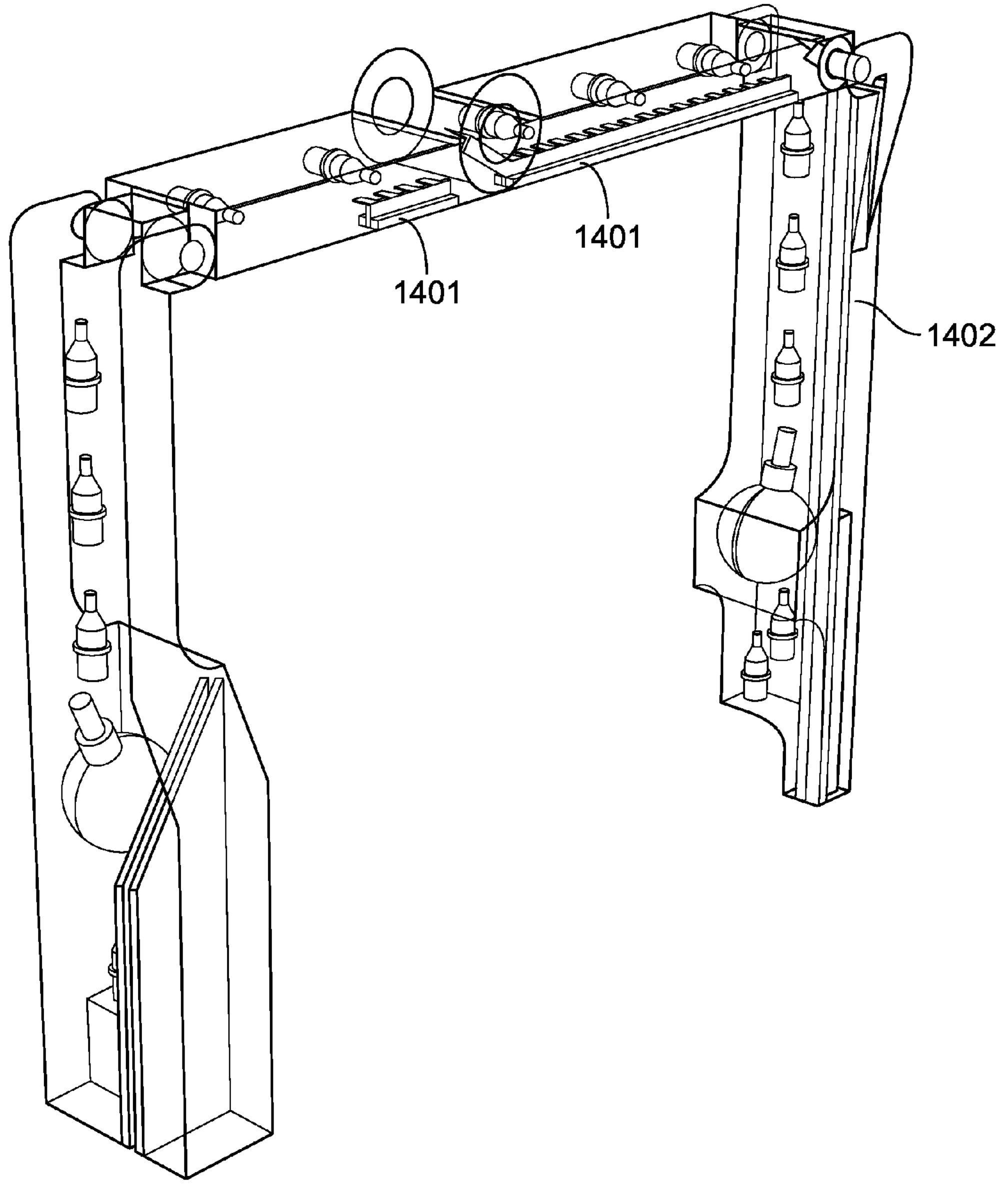


FIG. 13

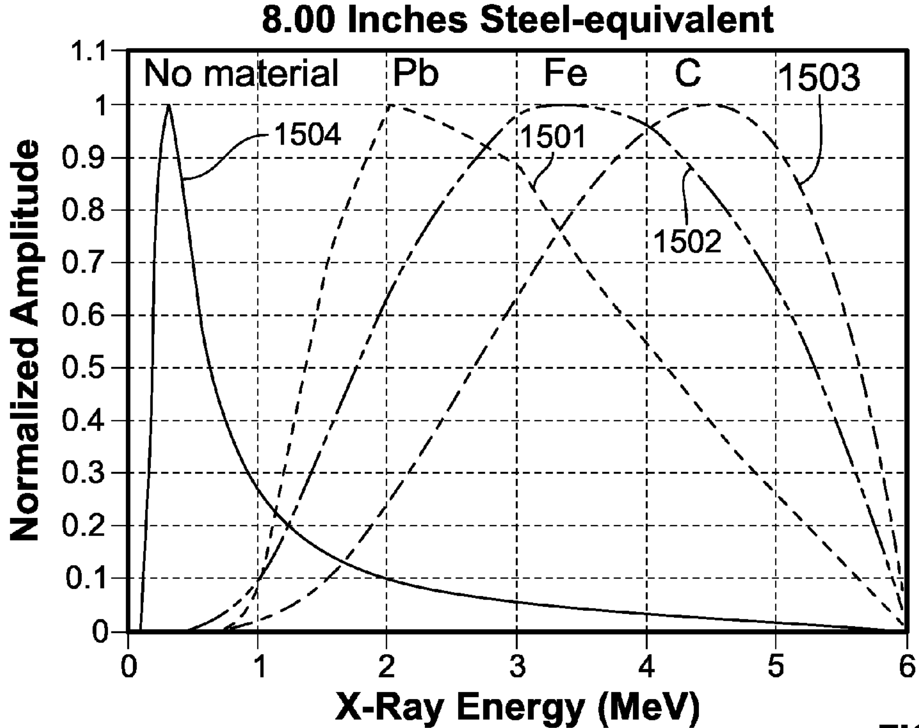

8.00 Inches Steel-equivalent
No material
Pb
Fe
C
1503
1504
1501
1502
Normalized Amplitude
X-Ray Energy (MeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
1
2
3
4
5
6

FIG. 14

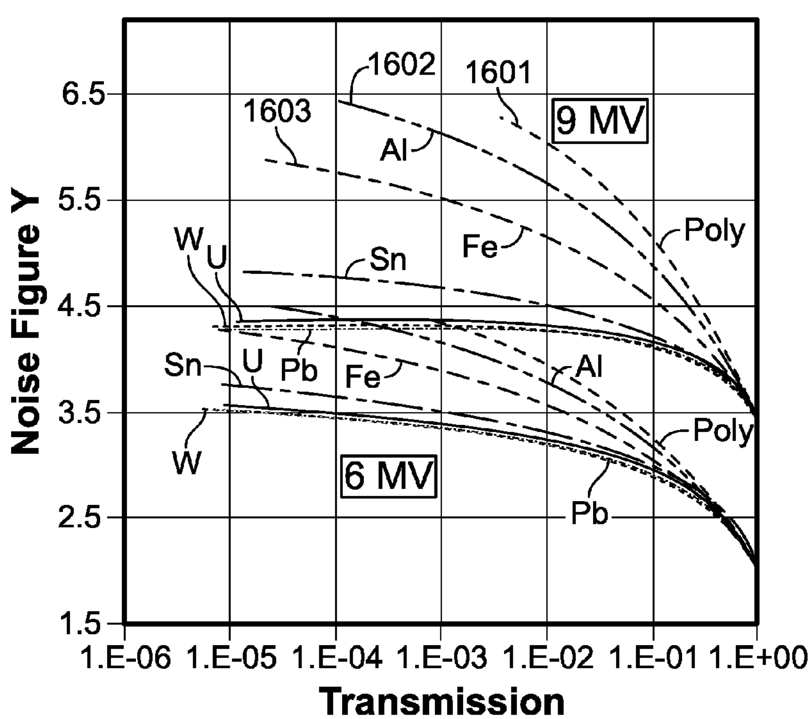

1602
1601
1603
9 MV
Al
Fe
Poly
W
U
Sn
U
Pb
Fe
Al
Sn
W
Poly
6 MV
Pb
Noise Figure Y
Transmission
6.5
5.5
4.5
3.5
2.5
1.5
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00

FIG. 15

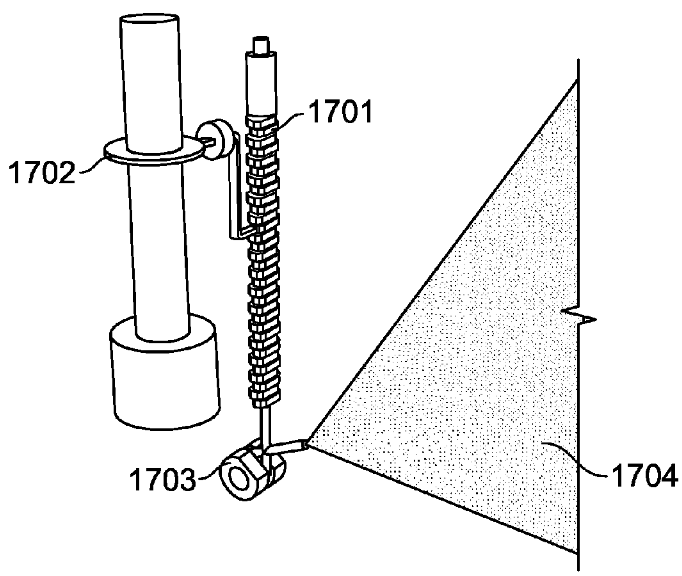

1701
1702
1703
1704

FIG. 16

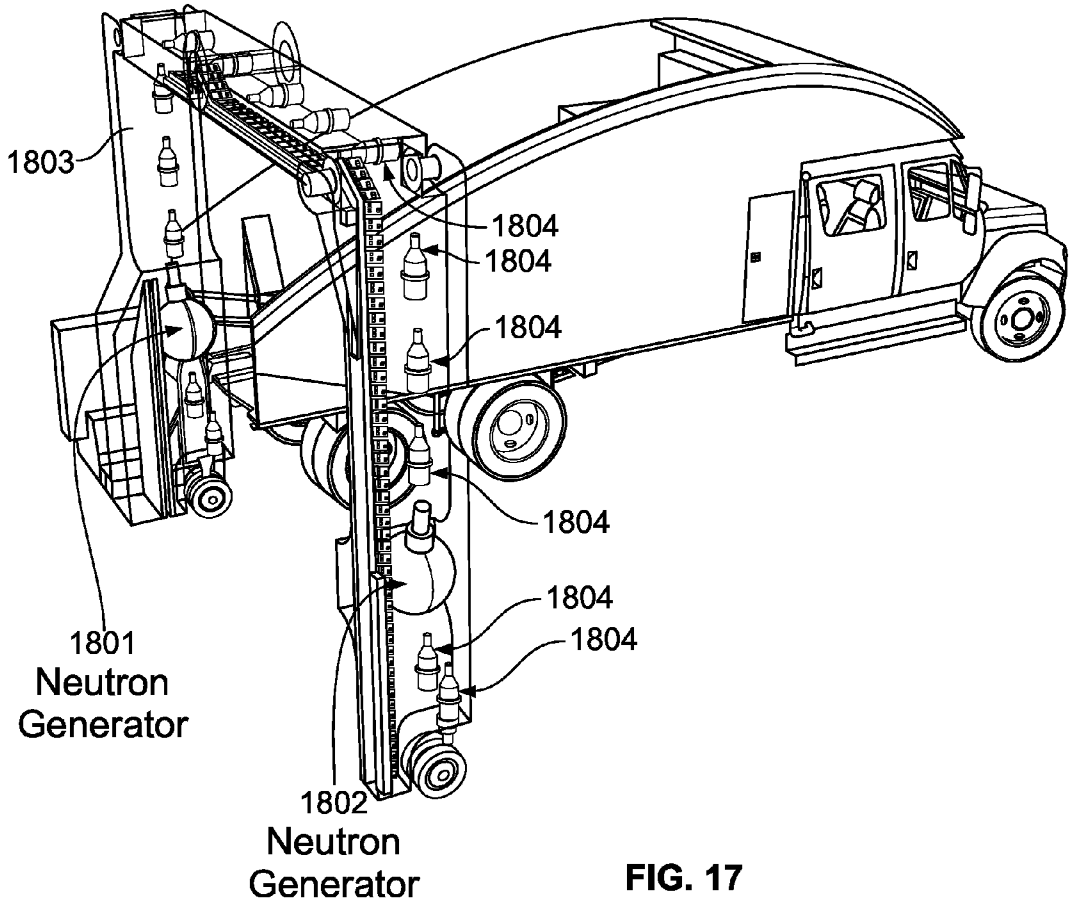
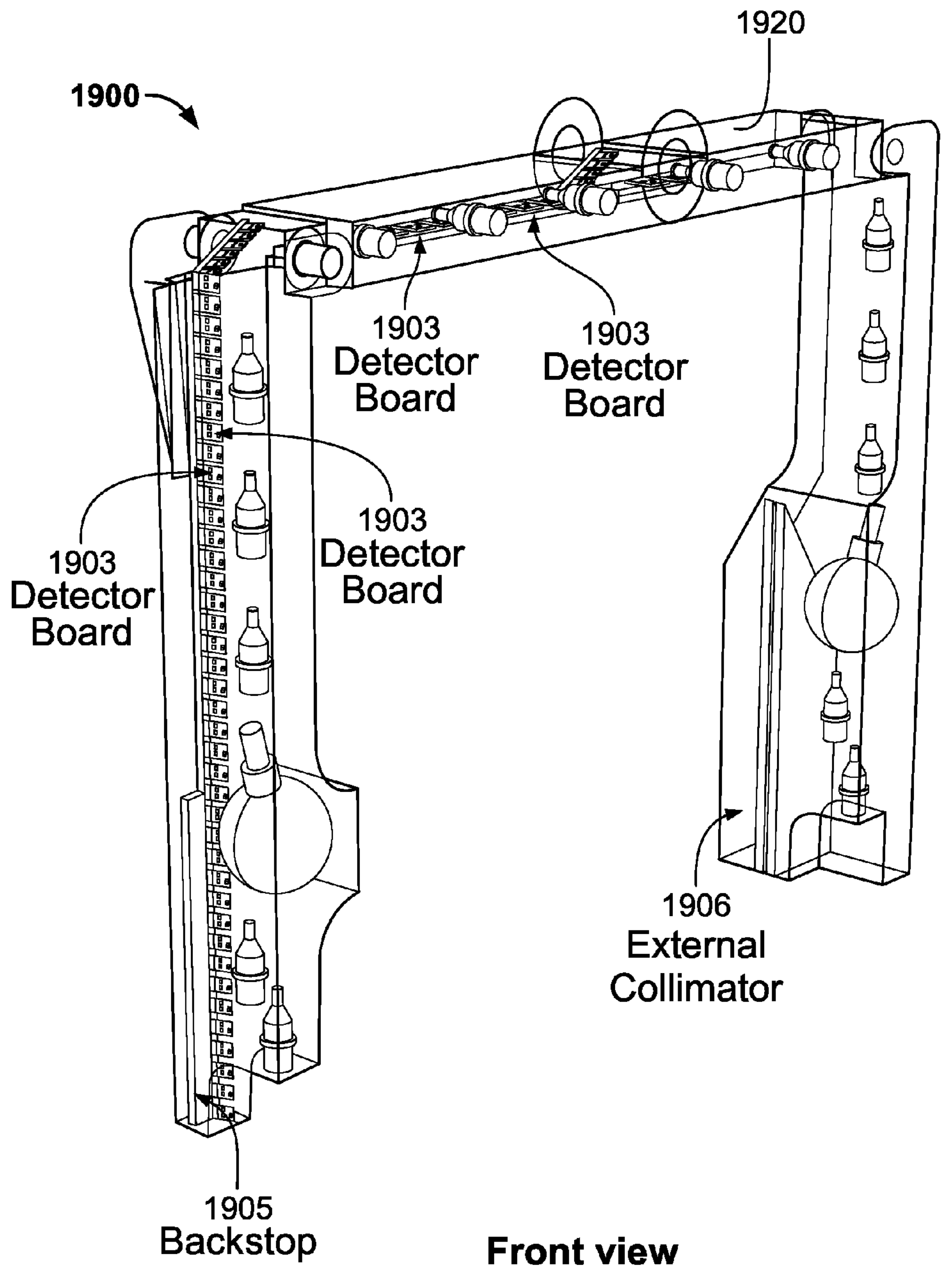
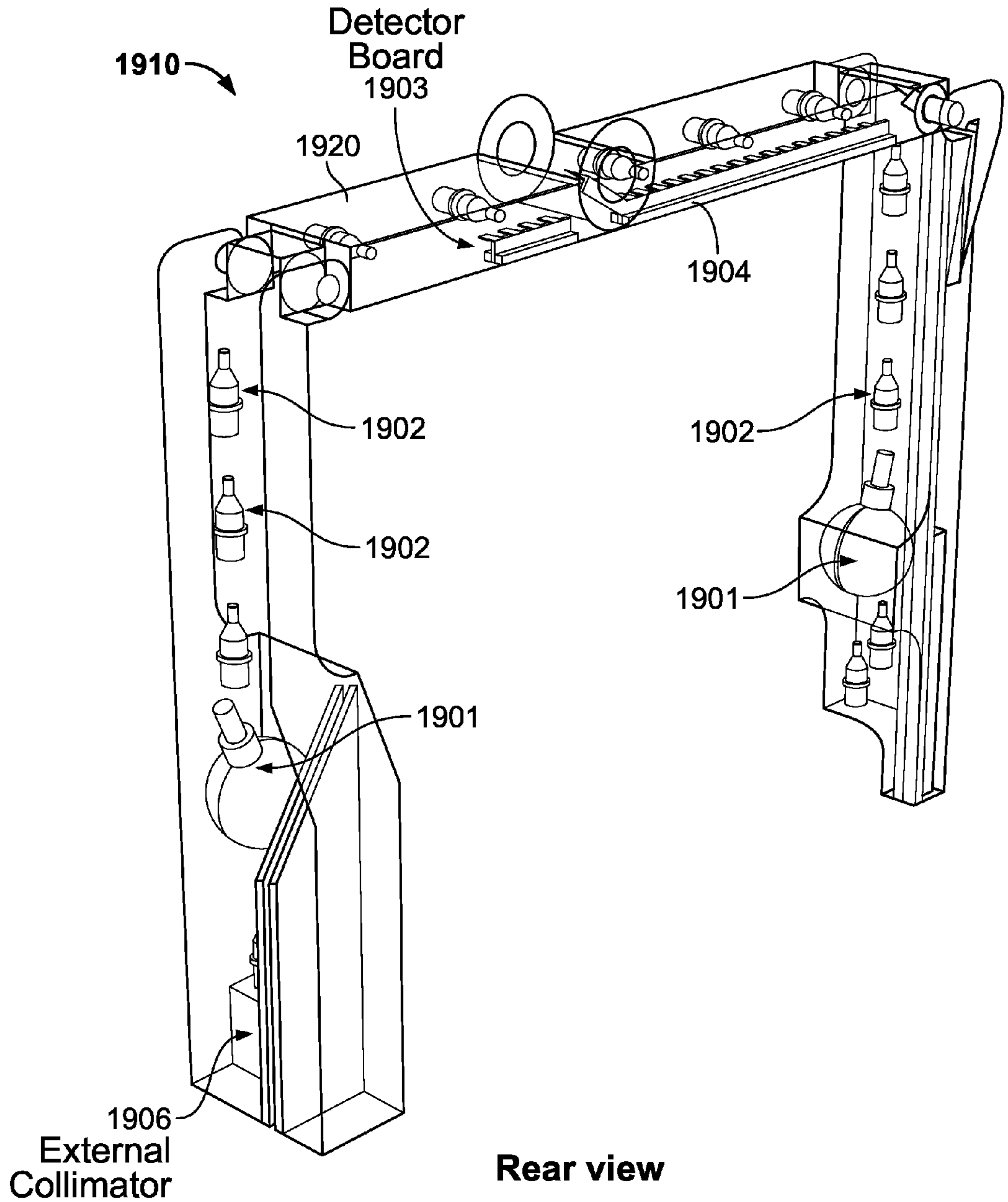

1803
1804
1804
1804
1804
1804
1804
1801
Neutron
Generator
1802
Neutron
Generator

FIG. 17



Front view

FIG. 18a



1910
Detector Board 1903
1920
1904
1902
1902
1902
1901
1901
1906 External Collimator
Rear view

FIG. 18b

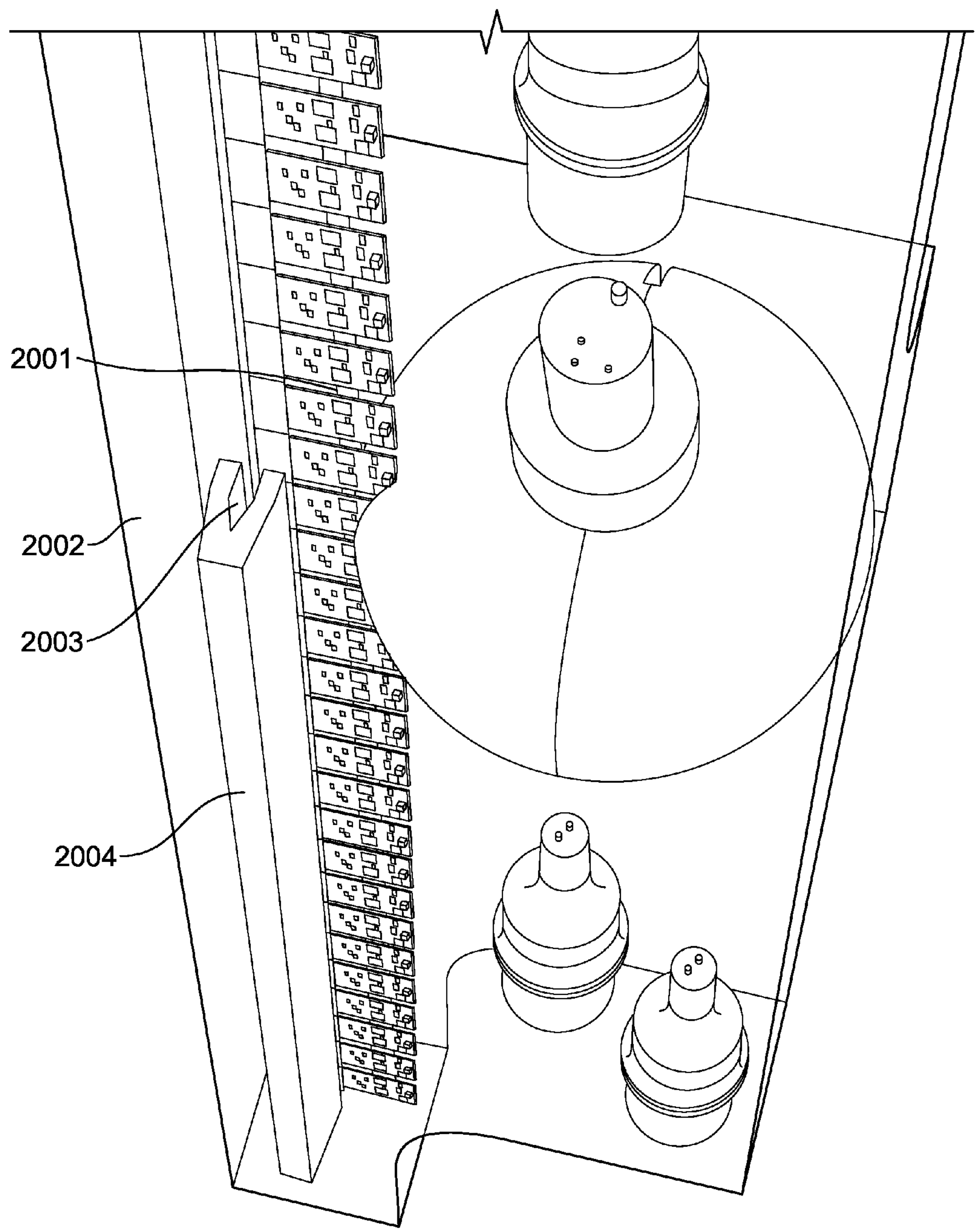


FIG. 19

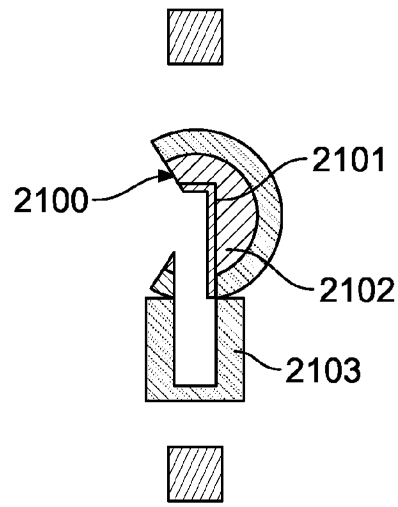


FIG. 20

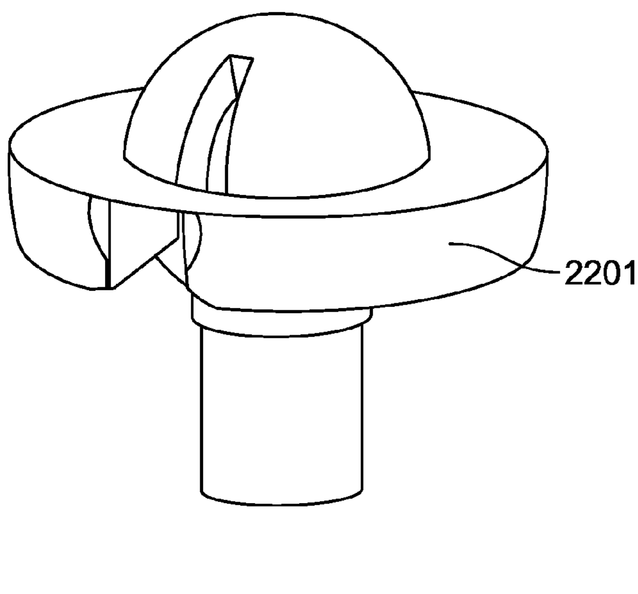


FIG. 21

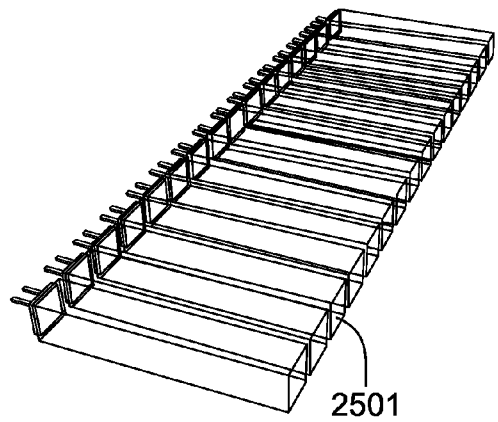


FIG. 22

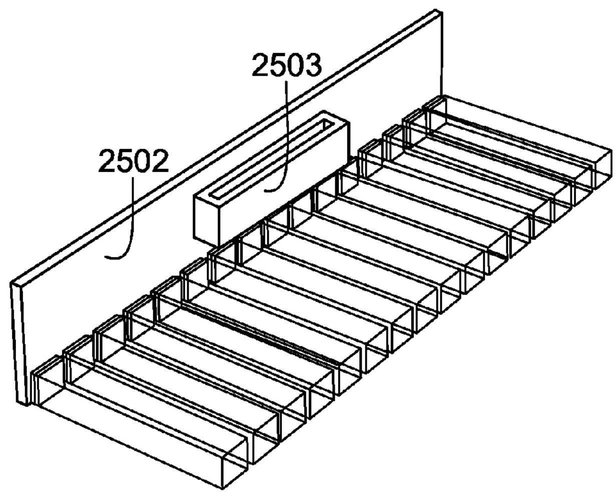


FIG. 23

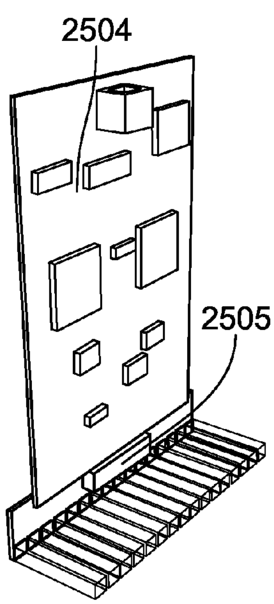


FIG. 24

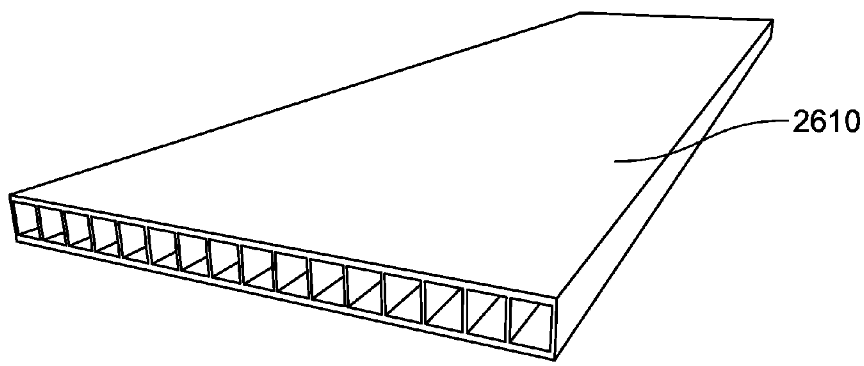


FIG. 25a

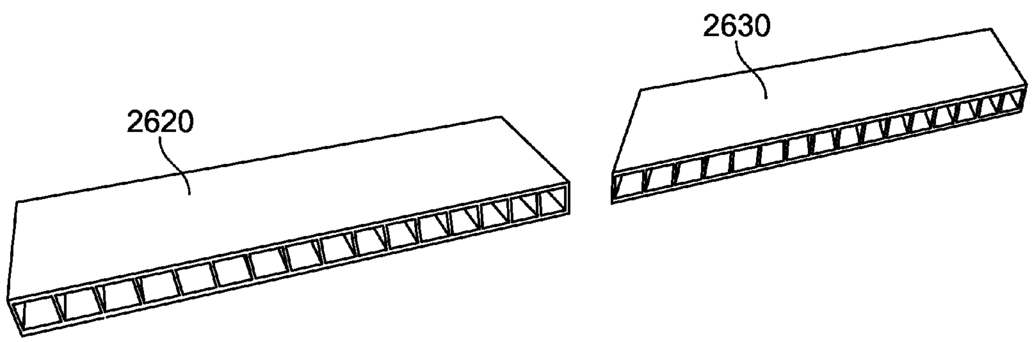


FIG. 25b

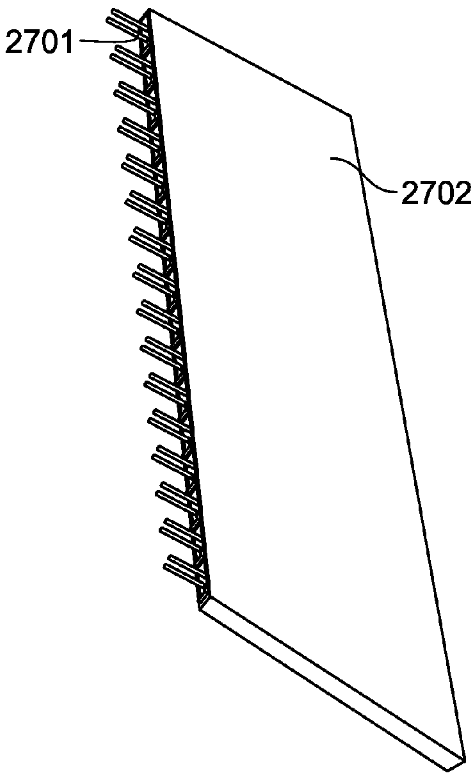


FIG. 26a

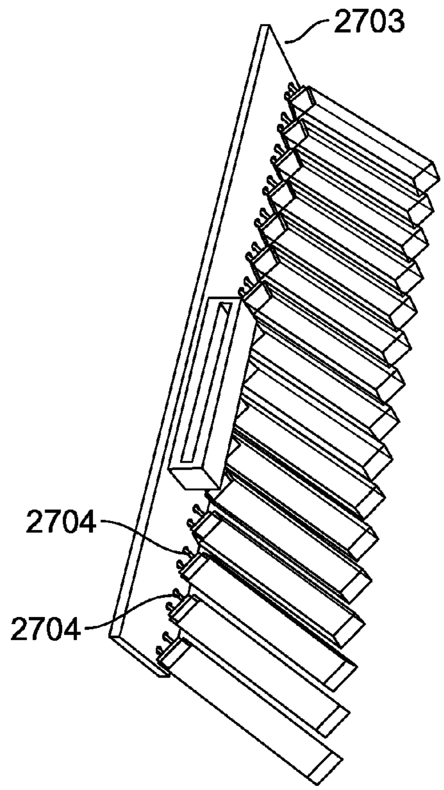


FIG. 26b

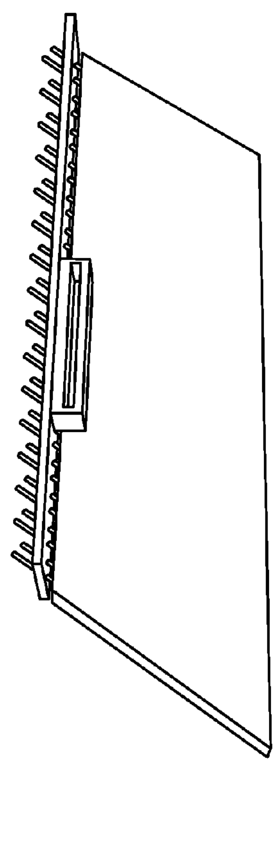


FIG. 26c

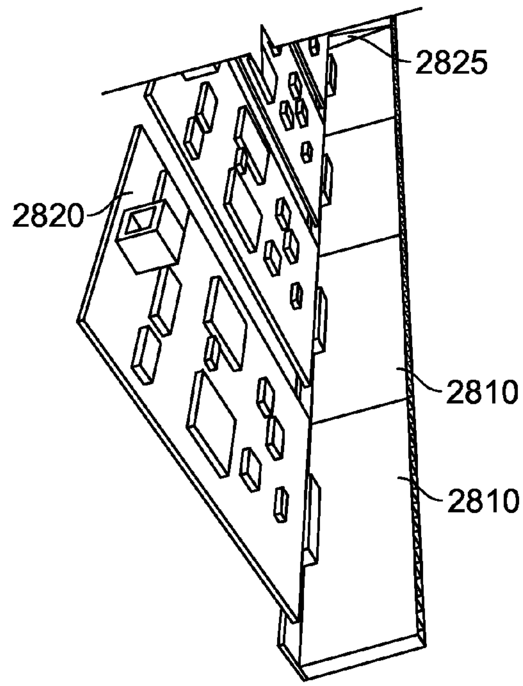


FIG. 27a

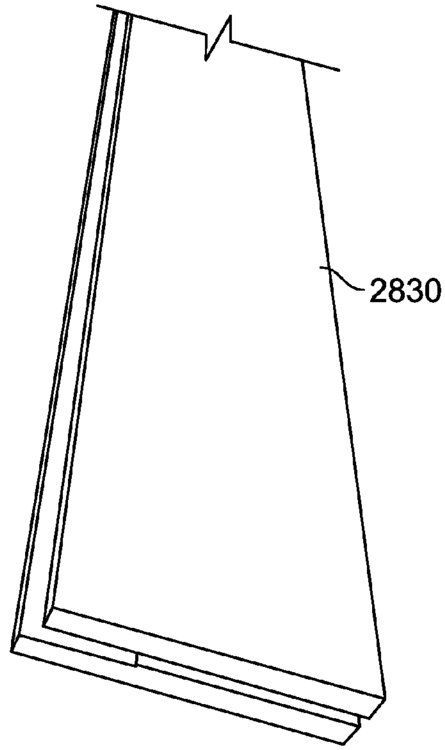


FIG. 27b

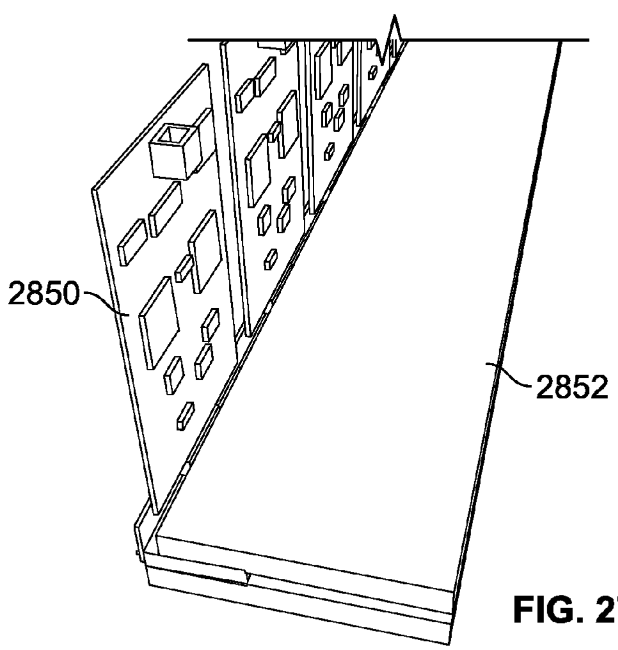


FIG. 27c

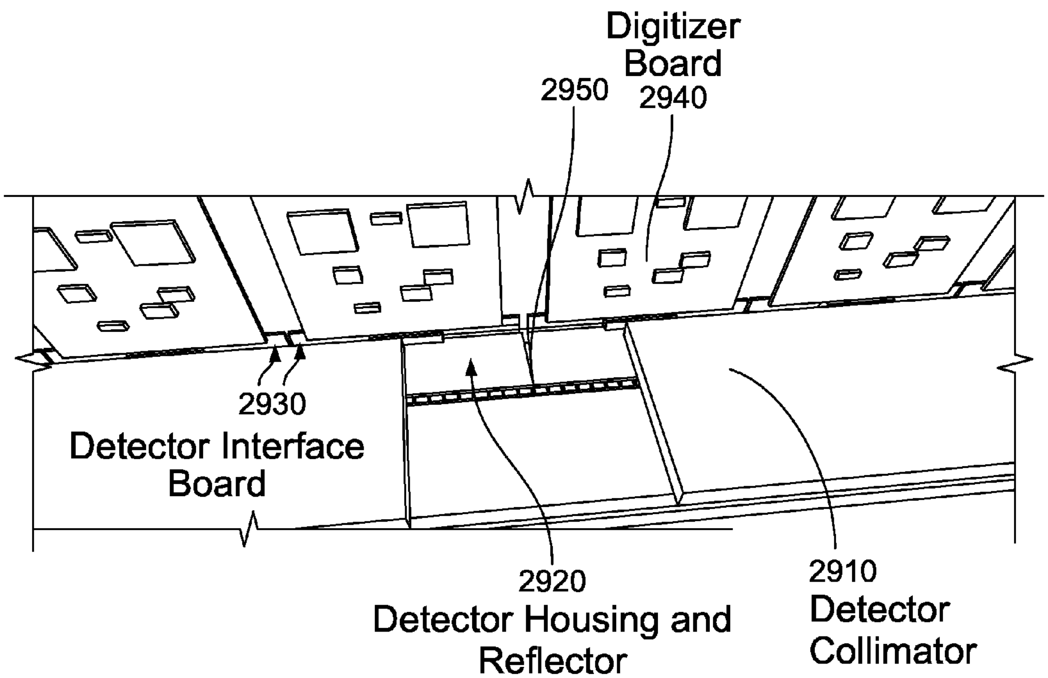

Digitizer Board
2950
2940
2930
Detector Interface Board
2920
Detector Housing and Reflector
2910
Detector Collimator

FIG. 28

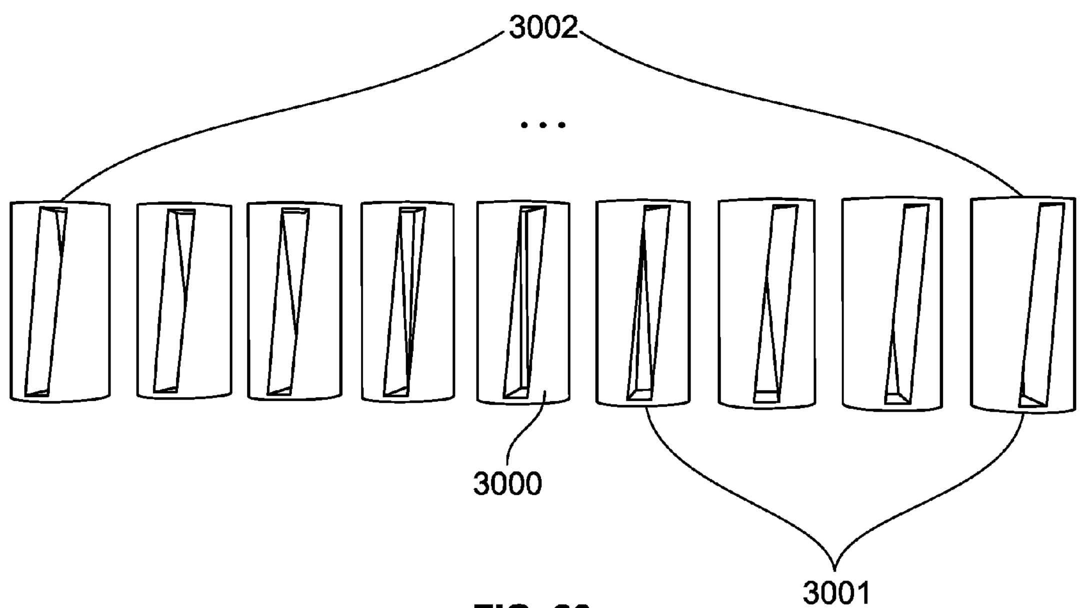


FIG. 29

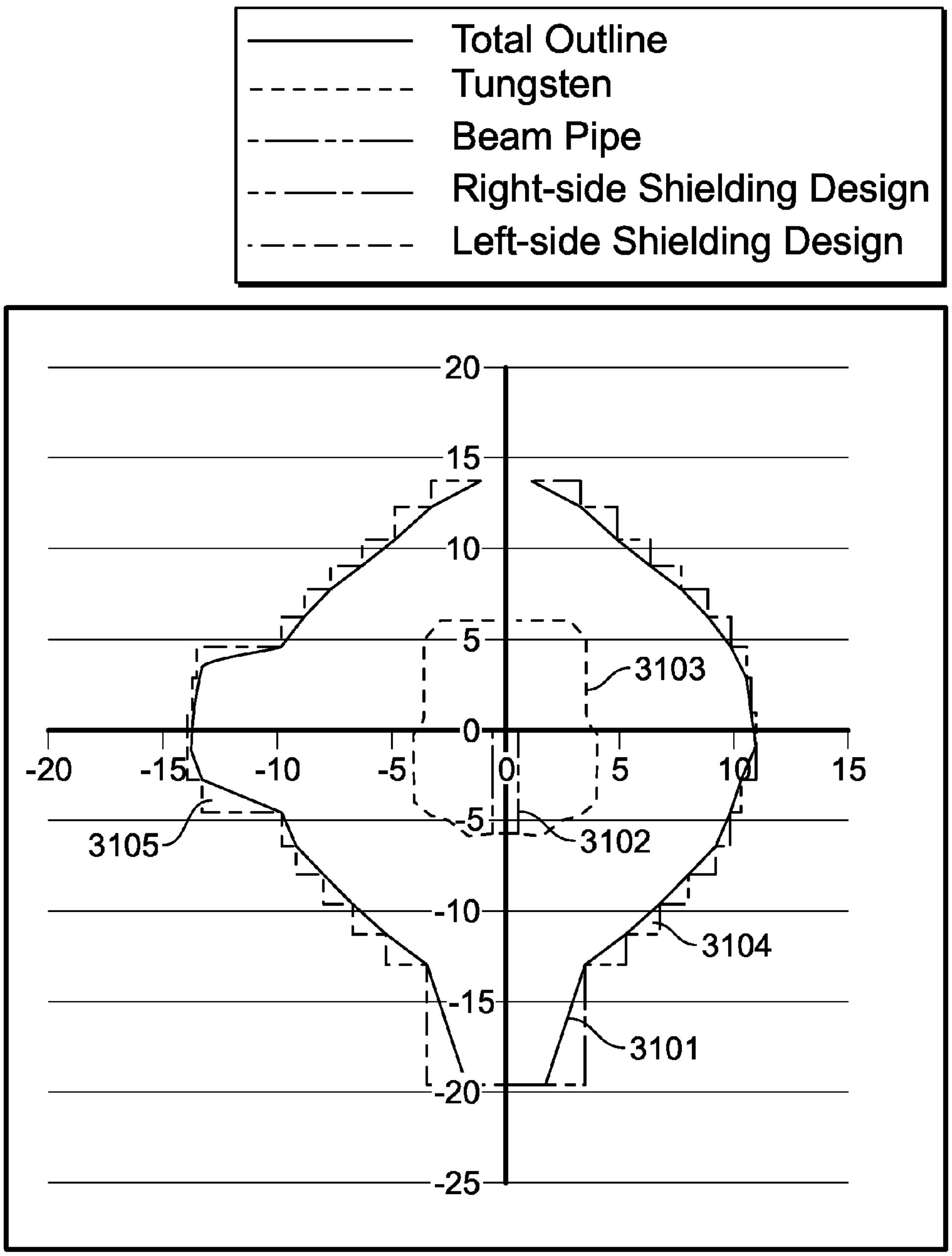

Total Outline
Tungsten
Beam Pipe
Right-side Shielding Design
Left-side Shielding Design
20
15
10
5
0
-5
-10
-15
-20
-25
-20
-15
-10
-5
0
5
10
15
3101
3102
3103
3104
3105

FIG. 30

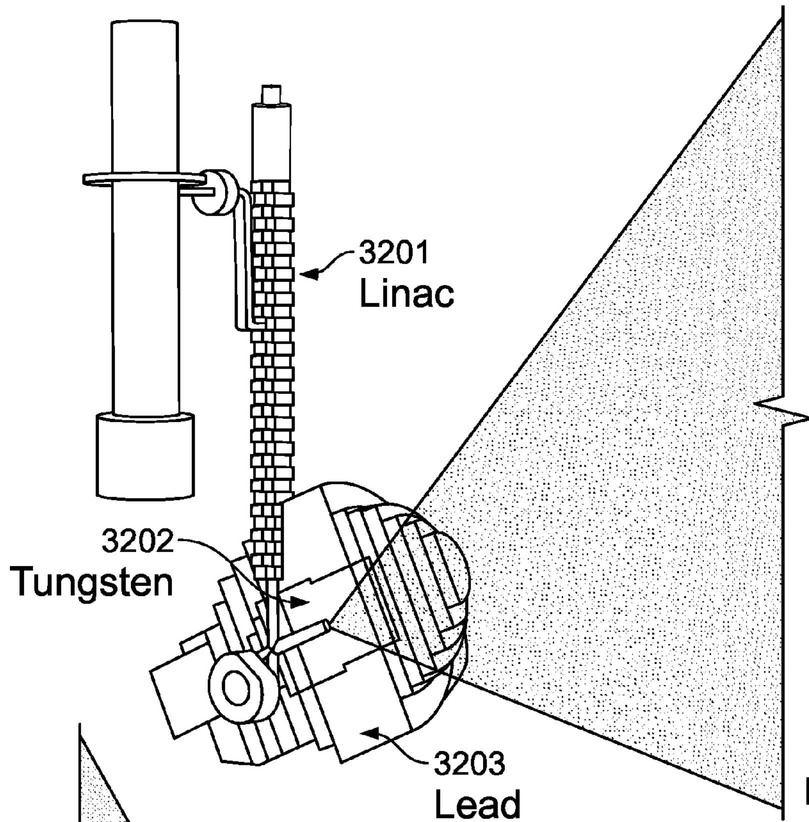


FIG. 31a

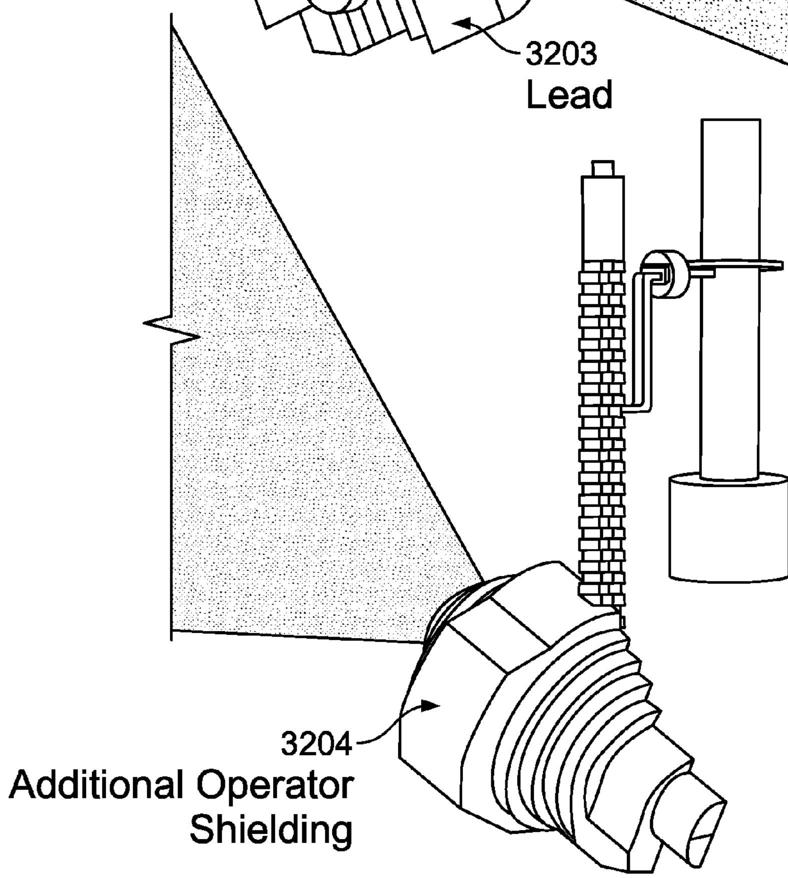
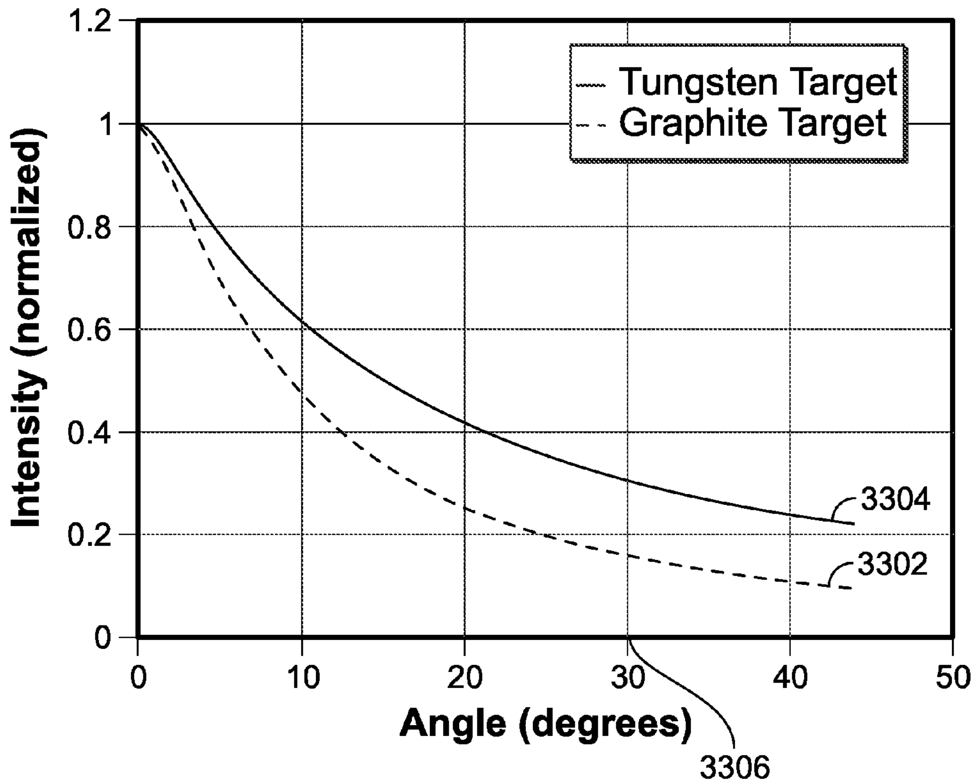
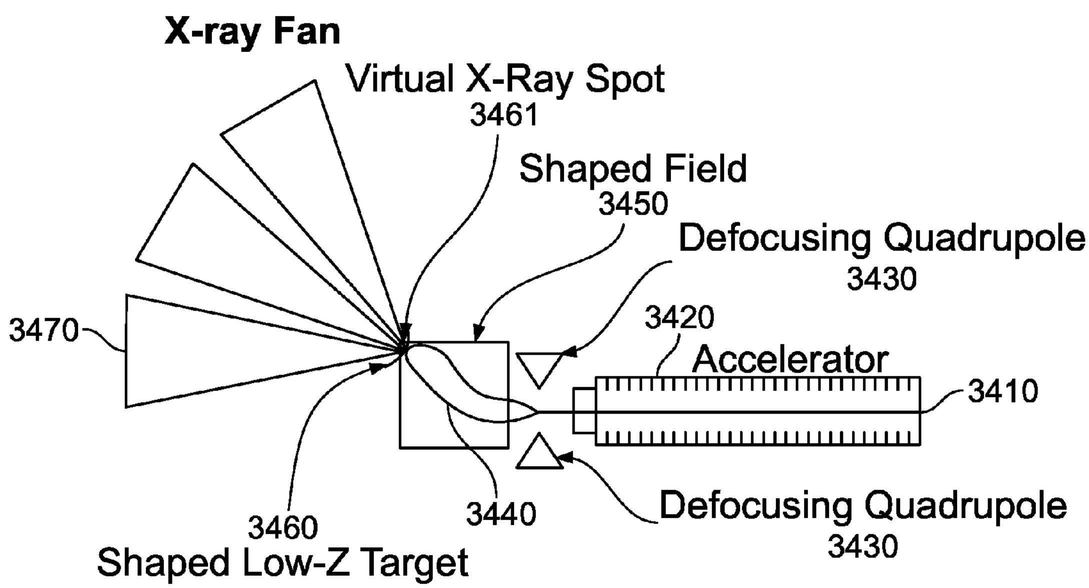


FIG. 31b



1.2
1
0.8
0.6
0.4
0.2
0
Intensity (normalized)
0
10
20
30
40
50
Angle (degrees)
Tungsten Target
Graphite Target
3304
3302
3306

FIG. 32



X-ray Fan
Virtual X-Ray Spot
3461
Shaped Field
3450
Defocusing Quadrupole
3430
3420
Accelerator
3410
3470
3460
3440
Shaped Low-Z Target
Defocusing Quadrupole
3430

FIG. 33

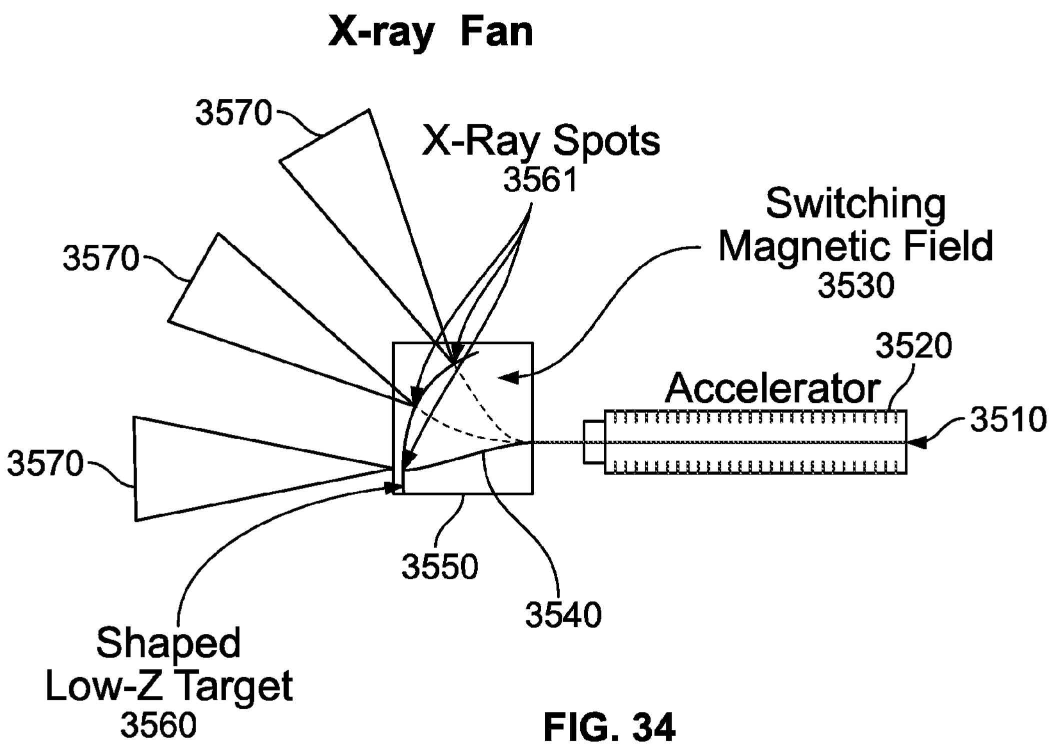


FIG. 34

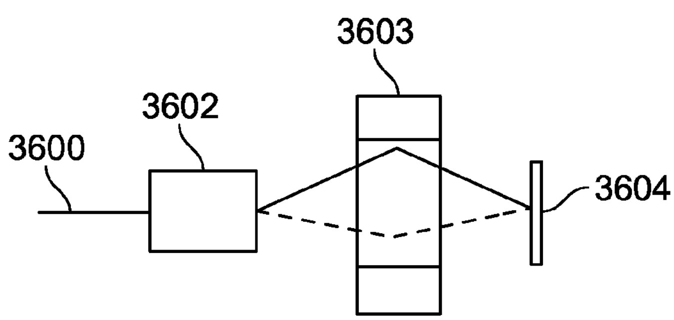


FIG. 35a

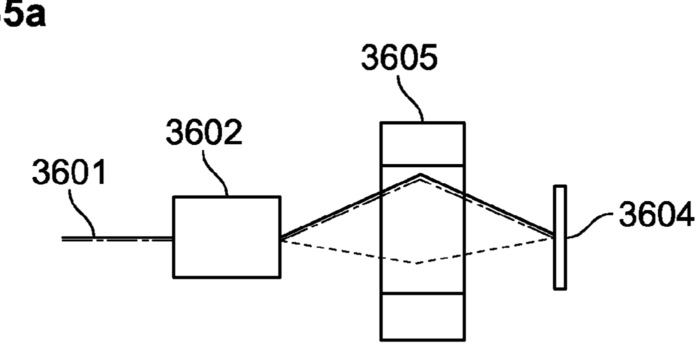


FIG. 35b

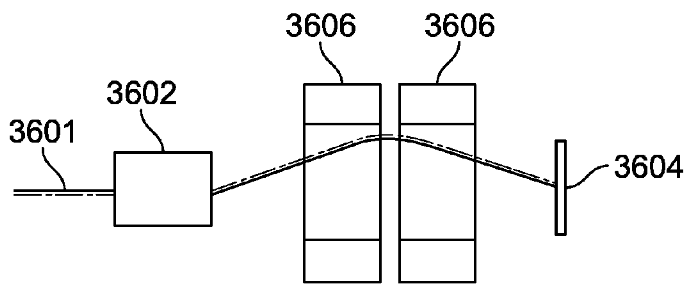


FIG. 35c

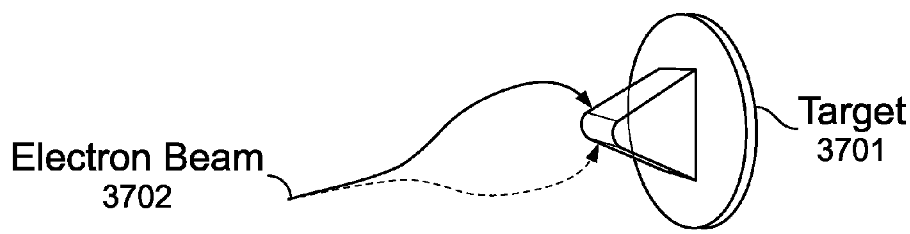


FIG. 36a

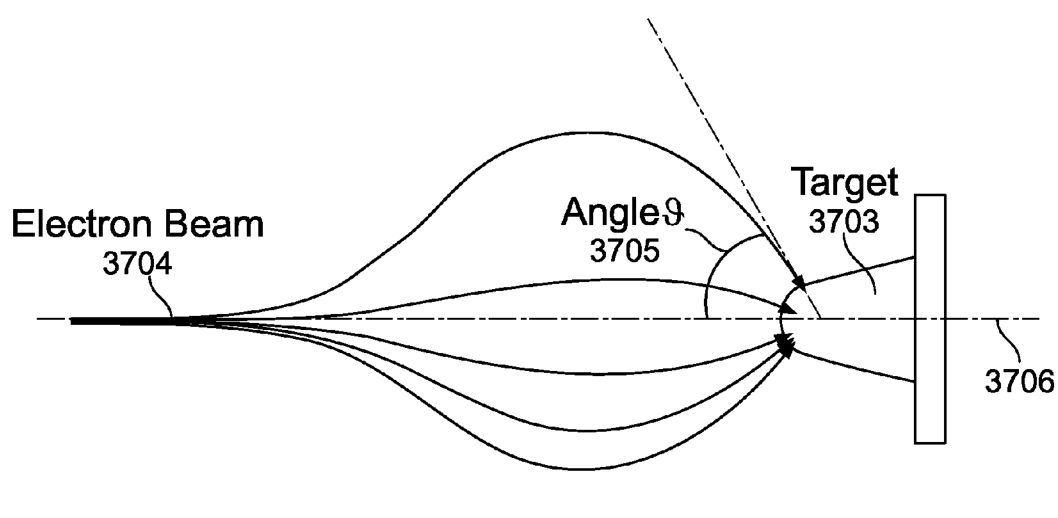


FIG. 36b

LOW-DOSE RADIOGRAPHIC IMAGING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

The present specification relies on U.S. Provisional Patent Application No. 61/880,159, entitled "Mobile Low-Dose Radiographic Imaging System", and filed on Sep. 19, 2013, for priority, which is herein incorporated by reference in its entirety.

The present specification is a continuation-in-part of U.S. patent application Ser. No. 13/492,614, entitled "System and Method for Reducing Weight of an X-Ray Source", and filed on Jun. 8, 2012, which, in turn, relies on Unites States Provisional Patent Application No. 61/494,887, filed on Jun. 9, 2011, which are herein incorporated by reference in their entirety.

The present specification is related to U.S. patent application Ser. Nos. 13/577,170; 14/104,625; 14/174,558; 14/228,340; 14/268,128; 14/293,258 all of which are hereby incorporated by reference in their entirety. The present specification is also related to U.S. Pat. Nos. 8,437,448; 8,054,937; 8,633,823; 8,724,744; 8,750,452; and 8,781,067 all of which are hereby incorporated by reference in their entirety.

FIELD

The present specification relates generally to X-ray imaging systems, and specifically to a mobile system for automatically and rapidly detecting the presence of high-atomic-number (high-Z) materials such as nuclear materials, radioactive materials, and shielding materials.

BACKGROUND

Security systems are presently limited in their ability to detect contraband, weapons, explosives, and other dangerous objects concealed in cargo. It is known in the art that images of various types of material can be generated by using various X-ray scattering and transmission techniques. The intensity of transmitted X-rays is related to the thickness, density and atomic number (Z) of the material scattering or absorbing the X-rays. Materials with high atomic number ($Z>70$) are characterized by the high attenuation of x-rays having energies in the high end of the X-ray spectrum, and in particular, energies in the range of 2-10 MeV, due to a process called e^+/e^- pair production. Therefore, X-ray transmission images are, in part, modulated by variations in the atomic number of items of various materials inside the cargo.

As a result of the image modulation due to the density, thickness and atomic numbers of various materials, it is common for X-ray imaging systems to produce images with dark areas. These dark areas might be indicative of the presence of threat materials; however, they yield little information about the exact nature of threat. In addition, radiographic images produced by conventional X-ray systems are often difficult to interpret because objects are superimposed. Therefore, a trained operator must study and interpret each image to render an opinion on whether or not a target of interest, or a threat, is present. Operator fatigue and distraction can compromise detection performance when a large number of such radiographic images are to be interpreted, such as at high traffic transit points and ports. Even with automated systems, it becomes difficult to comply with the implied requirement to keep the number of false alarms low, when the system is operated at high throughputs.

One method of obtaining more useful information and clarity from X-ray imaging is by using dual-energy systems to measure the effective atomic numbers of materials in containers or luggage.

Typical X-ray inspection systems include an X-ray generator which comprises a heated cathode filament emitting an electron beam. The emitted electrons are accelerated towards a target. The electron beam strikes the target at a focal spot and some portion of the kinetic energy contained within the electron beam is converted into X-rays. At the focal spot, the X-rays are emitted in all directions from the target surface, where the intensity and energy of X-rays varies based on the angle with respect to the electron beam direction. The generated X-rays are allowed to leave a heavily shielded area in a predefined direction through a collimator. Current x-ray inspection systems are very heavy, largely due to the massive amounts of shielding required to create the predefined area in which produced x-rays area allowed to propagate, such as in the forward direction where the X-rays are used for radiography or other purposes.

A greater amount of shielding is required when using electron targets made of materials having a high atomic number (high-Z). In contrast, low atomic number (low-Z) targets have a much more forward-peaked angular distribution, making it possible to eliminate a substantial amount of shielding. However, because of this forward-peaked angular distribution, when large areas need to be scanned, such as in mobile cargo radiography, the X-rays produced from low-Z targets typically do not cover the vertical extent of the object adequately. In addition, mobile cargo inspection systems typically require an X-ray source optimized for weight and performance. Currently, weight is primarily determined by the required quantity of shielding materials.

Furthermore, while mobile systems are available to provide inspection capabilities at locations which are constrained for space, such systems are generally large, heavy, and lack maneuverability. As a result these systems can be difficult to deploy quickly, especially in urban areas and pose several disadvantages and constraints.

Accordingly, there is still a need for improved inspection methods and systems built into a fully self-contained, smaller and more mobile vehicle that can be brought to any site accessible by roads and rapidly deployed for inspection. Moreover, there is an additional need for methods and systems that require minimal footprint with respect to the radiation dose to the environment, while still performing inspection using a sufficient range of the radiation energy spectrum to encompass safe and effective scanning of light commercial vehicles as well as cargo containers and trucks.

Additionally, there is a need for a system and method with reduced shielding requirements, thereby reducing the overall weight of an x-ray source employed in an x-ray inspection system, such as a mobile cargo inspection system.

Further, in the case of X-ray sources employing low Z targets, which require less shielding material but have limited capability in scanning the full vertical length of the object, there is a requirement for systems and methods to enhance the vertical scanning capability of such X-ray sources. What are also needed are systems and methods for deflecting the central point of an X-ray beam towards areas of high density in the scanned object.

In addition, there is also a need for an integrated X-ray inspection system further comprising a secondary scanning system such as a neutron subsystem to improve the material separation capability of the system.

SUMMARY

In some embodiments, a system for scanning cargo and vehicles is disclosed. In some embodiments, the operational flexibility of the system may be enhanced by significantly reducing its size and weight as compared to currently available mobile radiographic inspection systems. In some embodiments, the inspection system is mobile.

In some embodiments, the present specification describes an X-ray source comprising: an electron beam generator, wherein said electron beam generator generates an electron beam; an accelerator for accelerating said electron beam in a first direction; a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements; wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that the target substantially only generates X-rays focused toward a high density area in the scanned object.

In some embodiments, the high density section in the scanned object may be estimated in a second pulse using image data captured by a detector array in a first pulse and wherein the direction of electron beam is optimized by said X-ray source during said second pulse to focus X-rays towards said high density area in the scanned object based on said image data in said first pulse.

Optionally, the intensity of the electron beam may be optimized in each pulse to ensure that targeted areas in the scanned object are radiated with an optimal dose of X-rays.

Optionally, the magnetic field may cause said electron beam to strike the target at the same point but at a different angle in each successive pulse such that the angle at which said electron beam strikes the target depends on the position of the high density area in the scanned object.

Optionally, the magnetic field may cause said electron beam to strike the target at different points in successive pulses.

Optionally, the magnetic field may cause said electron beam to strike the target at the same point from different directions in successive pulses.

Optionally, the electron beam comprises single energy radiation. Optionally, said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise a dipole magnet. Still optionally, said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise a quadrupole magnet.

Optionally, the electron beam comprises dual energy radiation. Still optionally, the first set of magnetic elements may comprise a pulsed dipole magnet and the second set of magnetic elements may comprise a pulsed quadrupole magnet. Still optionally, the first set of magnetic elements may comprise a pulsed dipole magnet and the second set of magnetic elements may comprise two quadrupole magnets, wherein each quadrupole magnet is configured to transport at least one of the radiation energies in the dual energy radiation beam.

Optionally, the target may be manufactured from a material having low atomic number. Still optionally, the target may be manufactured from carbon, graphite or diamond.

Optionally, the target may be shaped. Still optionally, the target may be of a semi-circular, triangular, or flat shape.

Optionally, the source of the present specification may comprise shielding optimized to reduce the system weight.

Optionally, the linear accelerator is mounted in a substantially vertical direction.

In some embodiments, the present specification describes an X-ray source comprising: a generator for generating an electron beam; an accelerator for accelerating the generated electron beam in a desired direction; and, one or more magnetic elements for directing at least a part of the electron beam in at least one defined direction, wherein the magnetic elements comprise a defocusing magnet for directing a first part of the electron beam to a first predefined area within a shaped magnetic field and a second part of the electron beam to a second predefined area within the shaped magnetic field, wherein the first predefined area and second predefined area are different and wherein the shaped magnetic field directs the first and second parts of the electron beam onto a predefined area of a target, the directed parts of the electron beam producing a forward radiation at a plurality of different angles upon striking the said target.

In some embodiments, the present specification describes an inspection system for scanning cargo or vehicles comprising: an X-ray source for generating an electron beam; an accelerator for accelerating said electron beam in at least one predefined direction; a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements, wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that it substantially only generates X-rays focused toward a specific high density area in the scanned object; and, an X-ray detector array for detecting the radiation transmitted through the object under inspection.

Optionally, the inspection system may be mounted on a mobile inspection vehicle. Optionally, the inspection system further comprises a foldable boom which can be deployed to form a portal for cargo or vehicles to pass through. Still optionally, the foldable boom comprises a first vertical section, a second vertical section and a horizontal section, wherein the first vertical section is coupled to the inspection vehicle, and wherein a distal end of the first vertical section is coupled to a proximal end of horizontal section and a distal end of the horizontal section is coupled to a proximal end of the second vertical section. Still optionally, the first vertical section and second vertical sections are respectively coupled to wheels to support movement of boom structure. Still optionally, an outrigger wheel may be connected to the inspection vehicle and deployed before deploying the boom for added stability to the vehicle.

The X-ray source and the boom may be part of a single fixture that can be deployed or stowed. Optionally, the foldable boom assembly may be moved horizontally in range of 1 to 10 degrees, and preferably by 5 degrees, in either direction. Optionally, the inspection vehicle further comprises at least one operator station. Still optionally, the system may further comprise a neutron-based inspection subsystem comprising a pair of neutron generators and a plurality of gamma-ray detectors, wherein said X-ray detector array(s) and said neutron-based inspection subsystem are integrated within the boom.

In some embodiments, the high density area in the scanned object may be estimated in a second pulse using image data captured by the detector array in a first pulse and wherein the direction of electron beam is optimized by said X-ray source during said second pulse to focus X-rays towards said high density area in the scanned object based on said image data in said first pulse. Further, the intensity of electron beam may be optimized for each pulse to ensure that targeted areas in the scanned object are radiated with an optimal dose of X-rays.

Optionally, the magnetic field may cause said electron beam to strike the target at the same point but at a different angle in each successive pulse such that the angle at which said electron beam strikes the target depends on the position of high density area in the scanned object. Optionally, the magnetic field may cause the electron beam to strike the target at different points in successive pulses. Optionally, the magnetic field may cause the electron beam to strike the target at the same point from different directions in successive pulses.

Optionally, the electron beam comprises single energy radiation. Still optionally, the first set of magnetic elements may comprise a pulsed dipole magnet and said second set of magnetic elements may comprise a quadrupole magnet.

Optionally, the electron beam may comprise dual energy radiation. Still optionally, the first set of magnetic elements may comprise a pulsed dipole magnet and said second set of magnetic elements may comprise a pulsed quadrupole magnet. Still optionally, the first set of magnetic elements may comprise a pulsed dipole magnet and a second set of magnetic elements may comprise two quadrupole magnets wherein each quadrupole magnet is configured for transporting at least one of the radiation energies in the dual energy radiation beam.

Optionally, the target may be manufactured from a material having low atomic number. Still optionally, the target may be manufactured from carbon, graphite, or diamond.

Optionally, the target is shaped. Still optionally, the target may be of a semi-circular, triangular, or flat shape.

Optionally, the system further comprises shielding optimized to reduce the system weight.

Optionally, the X-ray source may be a linear accelerator mounted in a substantially vertical direction.

Optionally, the system may further conduct transmission Z-spectroscopy to analyze at least one material contained in the scanned object. Optionally, the system may further conduct noise spectroscopy to analyze at least one material contained in the scanned object.

Optionally, the system may further comprise at least one X-ray filter for vertically modulating x-ray intensity.

Optionally, the detector array may comprise one or more gapless X-ray detector arrays to detect the radiation transmitted by the scanned objects. The gapless detector array may comprise a two-dimensional array of small detector elements and wherein each detector element comprises a scintillator. Still optionally, the scintillator is a photo-sensing device, comprising at least one of: a photodiode, a biased photodiode, an avalanche photodiode, or a silicon multiplier. Optionally, the scintillator material may be LYSO, lead tungstate or any other suitable material. The detector array may be coupled to a collimator.

In some embodiments, the present specification describes an X-ray source comprising: an electron beam generator, wherein said electron beam generator generates an electron beam; an accelerator for accelerating said electron beam in a first direction; and, a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements, wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that the target generates X-rays, wherein a majority of the X-rays are focused on a high density section in the scanned object and a minority of the X-rays are focused elsewhere.

In some embodiments, the present specification describes an X-ray source comprising: an accelerator capable of generating pulsed electron beams of two or more different energies moving in a pre-defined direction, wherein at least a first pulse and a second pulse are generated; and, a set of electron steering components which causes the beam to strike the same area of the target at pre-defined angles, wherein said angle is estimated from at least one image captured from said first pulse of said electron beam.

In some embodiments, the present specification describes an X-ray source comprising: an accelerator capable of generating a sequence of pulsed electron beams of two or more different energies moving in a pre-defined direction, wherein a first pulse is low energy, a second pulse is high energy and each subsequent pulse in the sequence alternates between low energy and high energy; and, a set of electron steering components which causes the beam to strike the same area of the target at pre-defined angles, wherein said angle is estimated from at least one image captured from any previous pulse in the sequence of pulses of said electron beam.

Optionally, the steering components include a pulsed steering magnet and a pulsed quadrupole. Optionally, the steering components include a pulsed steering magnet and at least one DC magnet.

Optionally, the low energy beam ranges from 4 MeV to 6 MeV and the high energy beam ranges from 6 MeV to 10 MeV.

Optionally, the target is fabricated from tungsten, a low-z material such as graphite, or copper depending upon the application.

In some embodiments, the present specification describes an X-ray source comprising: an electron beam generator for generating an electron beam; an accelerator for accelerating the generated electron beam in at least one direction; and, one or more magnetic elements for directing a first part of the electron beam in a first direction and a second part of the electron beam in a second direction, wherein the first and second direction are different, wherein said directed parts of the electron beam produce a beam of X-rays upon striking a target.

Optionally, said first part of the electron beam and said second part of the electron beam strike the target at substantially the same point in a given pulse. Optionally, the directed parts of the electron beam may produce forward radiation at a plurality of different angles upon striking the target, providing a wide angular coverage of an object being scanned.

In some embodiments, the target may be shaped, allowing for the directed parts of the electron beam produce X-rays in one or more pre-defined directions.

Optionally, the magnetic elements may comprise a defocusing magnet for transporting at least a part of the electron beam to a predefined area within a shaped magnetic field, the shaped magnetic field directing the part of the electron beam onto a predefined part of the target.

Optionally, the target may be semi-circular, triangular, or flat. Optionally, the target is made from a material having a low atomic number such as carbon, graphite, or diamond.

In another embodiment, the present specification describes a mobile inspection system for scanning cargo or vehicles, the system mounted on an inspection vehicle, comprising: an X-ray source for producing radiation in the direction of an object to be inspected; a foldable boom which can be deployed to form a portal for cargo or vehicles to pass through; and an X-ray detector array for detecting the radiation transmitted through the object under inspection.

In some embodiments, the present specification discloses an inspection system for scanning cargo or vehicles, comprising: an X-ray source sub-system for producing a fan beam of radiation in the direction of an object to be inspected; and an X-ray detector array for detecting the radiation transmitted through the object under inspection. Optionally, the X-ray source sub-system may be vertically mounted.

Optionally, the inspection system may be mobile. Still optionally, the inspection system may comprise a foldable boom which can be deployed to form a portal for cargo or vehicles to pass through. Optionally, the size and weight of the inspection vehicle may be reduced by employing a hybrid fuel-electric vehicle.

In some embodiments, the present specification is directed toward a mobile inspection system for scanning cargo or vehicles, the system mounted on an inspection vehicle, comprising: a vertically mounted X-ray source sub-system for producing a fan beam of radiation in the direction of an object to be inspected; a foldable boom which can be deployed to form a portal for cargo or vehicles to pass through; and an X-ray detector array for detecting the radiation transmitted through the object under inspection.

Optionally, the X-ray source and boom are part of a single fixture that can be deployed or stowed.

In some embodiments, the foldable boom may comprise a first vertical section, a second vertical section and a horizontal section, wherein the first vertical section is coupled to the inspection vehicle; the distal end of the first vertical section is coupled to the proximal end of horizontal section and the distal end of the horizontal section is coupled to the proximal end of the second vertical section. Optionally, the first vertical section and second vertical sections may be coupled to wheels to support the movement of boom structure. Optionally, the inspection vehicle may be coupled to a wheel that is deployed before deploying the boom and the X-ray source to lend stability to the inspection vehicle and/or to prevent the inspection vehicle from tilting backwards. Optionally, the foldable boom assembly may be rotated horizontally in range of 1 to 10 degrees, and preferably by 5 degrees, in either direction. Optionally, a neutron generator may be positioned on at least one side of the foldable boom to allow detection of threats on at least one side and/or the top of the object passing through the portal. In some embodiments, the inspection system may comprise at least one operator station.

In some embodiments, the X-ray source sub-system further comprises optimized shielding to reduce overall weight of the source.

Optionally, the intensity of the X-ray source is modulated to reduce the size of the exclusion zone.

Optionally, the X-ray source sub-system further includes an applied magnetic field.

Optionally, the X-ray source sub-system further comprises a bending magnet.

Optionally, the X-ray source sub-system may further comprise a low atomic number target. In some embodiments, the low atomic number target may comprise carbon. In some embodiments, the low atomic number target may comprise graphite. In some embodiments, the low atomic number target may comprise diamond. Optionally, the low atomic number target is shaped and may comprise a semi-circular, triangular, or flat shape.

In operation, an electron beam may be vertically steered onto the low atomic number target in the X-ray source sub-system. Optionally, the electron beam may be steered by use of a magnet, or by electrostatic deflectors, or by a combination of both. Optionally, the electron beam may be steered to adjust the direction of strongest emission of the X-rays towards the area of highest attenuation in the object under inspection.

Optionally, the inspection system may further employ transmission X-ray spectroscopy and/or noise spectroscopy to analyze the material contained in the scanned object.

Optionally, the inspection system further comprises X-ray filters to modulate the x-ray intensity vertically.

Optionally, the inspection system uses pulse-width modulation to change X-ray intensity. Optionally, the system uses pulse-height modulation to change X-ray intensity.

In some embodiments, the inspection system may further comprise at least one gapless X-ray detector arrays to detect radiation transmitted by the scanned objects. Optionally, the inspection system may use a two-dimensional array of small detector segments. In some embodiments, each detector segment in the array may be individually aligned to aim at the source. Optionally, different scintillator materials may be used for different detector segments.

Optionally, the detector array may comprise a plurality of long, thin detectors. Further, the long, thin detectors may comprise scintillation crystals with photo-detector elements. Optionally, the scintillator material may be LYSO. Still optionally, the scintillator material may be lead tungstate. In some embodiments, the photo-detector elements may comprise at least one of: photodiodes, biased photodiodes, avalanche photodiodes, or silicon photomultipliers.

Optionally, the detector array may be coupled to a collimator.

Optionally, the X-ray source is a high-duty factor X-ray source for improved material discrimination.

In some embodiments, the inspection system may further comprise a neutron-based inspection subsystem comprising a pair of neutron generators and a plurality of gamma-ray detectors, wherein said X-ray detector array(s) and said neutron-based inspection subsystem are integrated within the boom.

In some embodiments, the neutron subsystem may further comprise a three-layered shielding collimator. Optionally, the radiation footprint of the neutron subsystem is reduced by using direction-specific shielding.

In some embodiments, the present specification describes a mobile inspection system for scanning cargo or vehicles, the system mounted on an inspection vehicle, comprising: a vertically mounted X-ray source sub-system for producing a fan beam of radiation in a direction of an object to be inspected; a foldable boom which can be deployed to form a portal for cargo or vehicles to pass through; at least one X-ray detector array for detecting the radiation transmitted through the object under inspection; and a neutron-based inspection subsystem comprising one or more neutron generators and a plurality of gamma-ray detectors, wherein said X-ray detector array(s) and said neutron-based inspection subsystem are integrated within the boom.

In some embodiments, the present specification describes a mobile inspection system for scanning cargo or vehicles, the system mounted on an inspection vehicle, comprising: a vertically mounted X-ray source sub-system for producing a fan beam of radiation in a direction of an object to be inspected; a foldable boom which can be deployed and used to scan stationary cargo or vehicles by moving the inspection system; at least one X-ray detector array for detecting the radiation transmitted through the object under inspection; and a neutron-based inspection subsystem comprising one or more neutron generators and a plurality of gamma-ray detectors, wherein said X-ray detector array(s) and said neutron-based inspection subsystem are integrated within the boom.

In some embodiments, the present specification describes an X-ray source comprising: a generator for generating an electron beam; an accelerator for accelerating the generated electron beam in a desired direction; one or more magnetic elements for directing a first portion of the electron beam in a first direction and a second portion of the electron beam in a second direction, wherein the first and second direction are different; and wherein said directed portions of the electron beam produce a beam of X-rays upon striking a target.

Optionally, the target may be fabricated from a low atomic number material. Optionally, the target may be fabricated from carbon. Optionally, the target may be shaped. Still optionally, the target may be semi-circular, triangular, or flat.

Optionally, the directed portions of the electron beam may produce forward radiation at a plurality of different angles upon striking the shaped target, thereby providing a wide angular coverage of an object being scanned in one or more desired directions.

Optionally, the directed portions of the electron beam produce X-rays having a wide angular coverage of an object being scanned only in one or more desired directions, thereby reducing an X-ray shielding requirement in one or more undesired directions.

Optionally, the directed portions of the electron beam may produce X-rays for covering an object such that it is scanned with more uniform intensity and energy.

Optionally, the magnetic elements may comprise a defocusing magnet for transporting at least a portion of the electron beam to a predefined area within a shaped magnetic field, the shaped magnetic field directing the portion of the electron beam onto a predefined part of the shaped target, thereby causing production of X-rays in a desired direction.

Still optionally, the magnetic elements may comprise one or more quadrupole magnets for directing at least a portion of the electron beam to a predefined area within a shaped magnetic field, the shaped magnetic field directing the portion of the electron beam onto a predefined part of the shaped target, thereby causing production of X-rays in a desired direction.

Still optionally, the magnetic elements may comprise a bending magnet for transporting at least a portion of the electron beam to a predefined area within a shaped magnetic field, the shaped magnetic field directing the portion of the electron beam onto a predefined part of the shaped target, thereby causing production of X-rays in a desired direction. Optionally, the bending magnet is configured to transport a first portion of the electron beam to a first predefined area within a shaped magnetic field on a first pulse and a second portion of the electron beam to a second predefined area within the shaped magnetic field on a second pulse.

In some embodiments, the X-ray may be produced in a fan beam, wherein the resultant fan beam is forward-peaked, thereby reducing an amount of lateral shielding required to prevent the X-rays from escaping in an undesired direction.

Optionally, a shaped magnetic field may be arranged to direct one or more portions of the electron beam onto the shaped target causing the generated X-rays to appear as originating from within a predefined distance of a predefined point within the shaped target. Still optionally, a shaped magnetic field may be arranged to direct a plurality of portions of the electron beam to different areas on the shaped target, causing the generated X-rays to appear as originating from different points within the shaped target.

In some embodiments, the present specification describes an X-ray source, comprising: a generator for generating an electron beam; an accelerator for accelerating the generated electron beam in a desired direction; one or more magnetic elements for directing at least a portion of the electron beam in a desired direction, the magnetic elements comprising a defocusing magnet for directing a first portion of the electron beam to a first predefined area within a shaped magnetic field and a second portion of the electron beam to a second predefined area within the shaped magnetic field, wherein the first predefined area and second predefined area are different; and a target, the shaped magnetic field directing the portion of the electron beam onto a predefined area of the target, the directed parts of the electron beam producing a forward radiation at a plurality of different angles upon striking the target.

Optionally, the target may be fabricated from a low atomic number material. Optionally, the target may be fabricated from carbon, graphite or diamond. Optionally, the target may be shaped. Still optionally, the target may be semi-circular, triangular, or flat.

In some embodiments, the present specification describes an X-ray source comprising: a generator for generating an electron beam; an accelerator for accelerating the generated electron beam in a desired direction; and means for directing multiple portions of electron beam to strike different areas of a target to produce a beam of X-rays.

Optionally, the target may be fabricated from a low atomic number material. Optionally, the target may be fabricated from carbon. Optionally, the target may be shaped. Still optionally, the target may be semi-circular, triangular, or flat.

Optionally, said means comprise magnetic elements. Optionally, said means comprise shaping a magnetic field designed to transport different portions of a beam to strike different areas of a shaped target to produce a X-ray beam.

Optionally, the directed portions of the electron beam may produce forward radiation at a plurality of different angles upon striking the shaped target and thus, may provide wide angular coverage of an object being scanned in one or more desired directions.

Optionally, the X-ray source may further comprise means for directing the maximum intensity of the X-ray fan beam towards high attenuation areas of the scanned object.

Optionally, the X-ray source may further comprise means for modulating the intensity of the electron beam depending on the scanning requirement.

Optionally, the X-ray source may further comprise means to modify the electron beam direction and intensity based on the image data captured by the system.

Optionally, the X-ray source may further comprise a bend magnet which bends the electron beam on each alternative pulse thereby switching the electron beam from one direction on a target to another in successive electronic pulses.

In some embodiments, the present specification describes an X-ray source comprising: a generator for generating an electron beam; and an accelerator for accelerating the generated electron beam in a desired direction, wherein said electron beam is transported to different areas within a shaped magnetic field and wherein said shaped magnetic field is designed to transport different portions of the beam to strike different areas of a target to produce an X-ray beam.

Optionally, the target may be fabricated from a low atomic number material. Optionally, the target may be fabricated from carbon. Optionally, the target may be shaped. Still optionally, the target may be semi-circular, triangular, or flat.

In some embodiments, the present specification describes an X-ray source comprising: a generator for generating a dual energy electron beam; an accelerator for accelerating said dual energy electron beam in a desired direction; and a steering magnet to transport the said dual energy electron beam into a magnetic field created by a pulsed quadrupole magnet which causes said dual energy electron beam to strike a target at at least one predefined angle to focus the direction of generated X-rays towards areas of high attenuation in the scanned object, wherein said angle is estimated from the image captured in previous pulses by the X-ray system.

In some embodiments, the present specification describes an X-ray source comprising an accelerator capable of generating pulsed electron beams of two or more different energies moving in a desired direction and a set of electron steering components which causes the beam to strike the same area of a target at predefined angles, wherein said angle is estimated from the image(s) captured in previous pulse(s) of the x-ray beam. Optionally, the steering components may include a pulsed steering magnet and a pulsed quadrupole. Still optionally, the steering components may include a pulsed steering magnet and two or more DC magnets. In some embodiments, the low energy may be 6 MeV and the high energy is 9 MeV. In some embodiments, the low energy may be 4 MeV and the high energy may be 6 MeV.

Optionally, the target may be fabricated from tungsten for wide fan beams, low-Z materials, such as graphite for narrow fan beams, or copper for reducing the production of photo-neutrons.

In some embodiments, the present specification describes an X-ray inspection system for scanning cargo or vehicles, comprising: an X-ray source for producing a beam of radiation toward an object to be inspected; and a gapless X-ray detector array for detecting the radiation transmitted through the object under inspection.

Optionally, the gapless detector array may comprise a two-dimensional array of small detector elements wherein each detector element comprises a scintillator. Optionally, said scintillator may comprise a photo-sensing device. Optionally, for a given angle of incidence, a virtual detector comprising a certain combination of said detector elements may be representative of the signal in that direction.

The aforementioned and other embodiments of the present shall be described in greater depth in the drawings and detailed description provided below.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present specification will be appreciated, as they become better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIG. **1** illustrates a side view of an exemplary mobile inspection system described in the present specification, according to an embodiment;

FIG. **2** illustrates a boom and X-ray source assembly mount, according to an embodiment of the present specification;

FIG. **3** illustrates an optional outrigger wheel, according to an embodiment of the present specification;

FIG. **4** illustrates another side view, including boom wheels, for the mobile inspection system of the present specification, shown in FIG. **1**;

FIG. **5***a* illustrates a boom stowing position, according to an embodiment of the present specification;

FIG. **5***b* illustrates a boom stowing position, according to an embodiment of the present specification;

FIG. **5***c* illustrates a boom stowing position, according to an embodiment of the present specification;

FIG. **5***d* illustrates a boom stowing position, according to an embodiment of the present specification;

FIG. **5***e* illustrates a boom stowing position, according to an embodiment of the present specification;

FIG. **5***f* illustrates a boom stowing position, according to an embodiment of the present specification;

FIG. **6** illustrates the mobile inspection system of the present specification during a scanning operation;

FIG. **7** shows an inverted-L-shaped detector array, as used in cargo inspection systems;

FIG. **8** illustrates a standard mounting configuration of detectors modules;

FIG. **9** illustrates a detector module mounting configuration for detector arrays that are constricted to a narrow vertical enclosure;

FIG. **10** is an illustration of a detector array consisting of a set of detector elements arranged in columns and rows both horizontally and vertically, where a particular set of detector elements can be chosen at every angle, which, as a set, is aligned to aim at the source;

FIG. **11** is a diagram depicting X-rays emanating from the source intersecting with the detector array shown in FIG. **10** at different angles;

FIG. **12** is a graph comparing light collection efficiency for small detectors versus large detectors, and the dependency on photodiode size;

FIG. **13** shows detector-collimator assemblies integrated within a boom structure, according to an embodiment of the present specification;

FIG. **14** is a graph showing energy spectra for various materials;

FIG. **15** is a graph showing a noise figure for various materials calculated according to a noise spectroscopy-based technique;

FIG. **16** is a depiction of an exemplary high-duty factor, vertically mounted X-ray source;

FIG. **17** illustrates an exemplary neutron subsystem, according to an embodiment of the present specification;

FIG. **18***a* illustrates a front view of an X-ray scanning system co-located with a neutron scanning system within a boom structure, according to an embodiment of the present specification;

FIG. **18***b* illustrates a rear view of an X-ray scanning system co-located with a neutron scanning system within a boom structure, according to an embodiment of the present specification;

FIG. **19** is a detailed view of the detector arrays located on a vertical portion of the boom;

FIG. **20** shows a three-layered neutron moderator design, according to an embodiment of the present specification;

FIG. **21** is an illustration of directional shielding around the neutron moderator shown in FIG. **20**;

FIG. **22** illustrates an exemplary implementation of a detector array comprising a number of long, thin detectors;

FIG. **23** illustrates an exemplary configuration and location of a detector interface board (DIB);

FIG. **24** shows a data acquisition board interfacing directly with an edge connector of a DIB, according to an embodiment of the present specification;

FIG. **25***a* illustrates an exemplary extrudate that can be used to form a housing for detectors in a detector array, in an embodiment of the present specification;

FIG. **25***b* shows the extrudate of FIG. **25***a* cut at various angles to form detector housings, according to an embodiment;

FIG. **26***a* illustrates a detector assembly with a reflector and a DIB, according to an embodiment of the present specification;

FIG. **26***b* illustrates a detector assembly with a reflector and a DIB, according to an embodiment of the present specification;

FIG. **26***c* illustrates a detector assembly with a reflector and a DIB, according to an embodiment of the present specification;

FIG. **27***a* shows a detector array assembly, according to an embodiment of the present specification;

FIG. **27***b* shows a collimator, according to an embodiment of the present specification;

FIG. **27***c* is an illustration of detector assemblies inserted into a steel collimator, according to an embodiment of the present specification;

FIG. **28** shows a cross-sectional view of the detector assemblies inserted into the collimator shown in FIG. **27***b;*

FIG. **29** shows an embodiment of an x-ray filter design used for focusing the electron beam on areas of high density;

FIG. **30** is a graphical representation of a specialized shielding design for a particular configuration;

FIG. **31***a* shows one view of an exemplary shielding design, according to an embodiment of the present specification;

FIG. **31***b* shows another view of the exemplary shielding design shown in FIG. **31***a;*

FIG. **32** is a graph depicting the intensity of an x-ray source versus an x-ray source angle corresponding to two similar x-ray sources coupled with high-Z and low-Z targets in accordance with an embodiment of the present specification;

FIG. **33** illustrates an x-ray fan beam generated by using a low-Z target, in accordance with an embodiment of the present specification, in which DC magnetic elements comprising a defocusing magnet and shaped magnetic field are employed;

FIG. **34** illustrates an x-ray fan beam generated by using a low-Z target, in accordance with an embodiment of the present specification, in which switching magnetic elements comprising a shaped magnetic field are employed;

FIG. **35***a* illustrates a single-energy system for vertical intensity modulation which employs a pulsed bend magnet and a DC quadrupole magnet in accordance with an embodiment of the present specification;

FIG. **35***b* illustrates a dual-energy system for vertical intensity modulation which employs a pulsed bend magnet and a pulsed quadrupole magnet in accordance with an embodiment of the present specification;

FIG. **35***c* illustrates a beam steering mechanism in a dual energy system which employs pulsed bend magnet and two DC magnets in accordance with an embodiment of the present specification;

FIG. **36***a* illustrates the trajectory of an electron beam during vertical intensity modulation, which arrives at a specific point on the target from two different directions in subsequent pulses to generate X-rays focused towards areas of high density; and,

FIG. **36***b* is another illustration of the trajectory of an electron beam during vertical intensity modulation, which arrives at a specific point on the target from different directions in subsequent pulses to generate X-rays focused towards areas of high density.

DETAILED DESCRIPTION

The present specification describes a radiographic imaging system that is substantially smaller than existing systems and has a considerably reduced weight. The system also has a much smaller exclusion zone due to better beam collimation and use of an intensity-modulated X-ray source. In some embodiments, the radiographic imaging system is highly mobile.

In some embodiments, the system is equipped with an appropriate shielding design which reduces the X-ray source weight significantly. Some embodiments of a shielding design are described below with reference to FIGS. **30**, **31***a*, and **31***b*.

In some embodiments, the x-ray source is mounted vertically. In a vertically mounted configuration, the x-ray target can be positioned close to the ground; thus, the system can inspect small vehicles and commercial vehicles to automatically detect high-Z materials such as SNM (Special Nuclear Materials). In another embodiment, the system includes integrated nuclear radiation detectors that help detect unshielded and lightly shielded radioactive materials.

In some embodiments, the operational flexibility of the system is enhanced by significantly reducing its size and weight by employing a hybrid (such as diesel and electric) inspection vehicle.

In some embodiments, the system uses, in additional to a primary radiography system, a neutron-based secondary inspection system to clear or confirm threats.

In some embodiments, the system uses a gapless imaging array that avoids image artifacts seen in existing systems. Two different gapless embodiments are described below with reference to FIGS. **10** and **11** and FIGS. **24** to **28**.

In some embodiments, to reduce the size of the exclusion zone and to improve the X-ray energy spectrum, intensity modulation of the X-ray source is employed.

In some embodiments, the system uses a set of X-ray filters that modulate the x-ray intensity vertically such that the highest intensity X-rays will strike the part of the cargo with the highest attenuation, as described with reference to FIG. **29** below.

In some embodiments, the system employs vertically steering the electron beam onto a X-ray production target, in order for the maximum intensity of the X-rays to be directed towards the part of the cargo with the highest attenuation, as shown in and described with respect to FIG. **35***a* below. In some embodiments, the X-ray production target is made from a low-Z material. In some embodiments, the low-Z X-ray production target is specially shaped. In some embodiments, the low-Z X-ray production target is carbon. In some embodiments, the low-Z X-ray production target is graphite. In some embodiments, the low-Z X-ray production target is diamond, which has specific cooling properties in that it is a good heat conductor.

In some embodiments, the present specification describes an x-ray inspection system employing a low-Z x-ray target in order to reduce shielding requirements and thereby reduce the overall weight of a linear accelerator x-ray source employed in the inspection system. Since X-rays generated from a low-Z target are more forward-peaked than those generated from a high-Z target, they allow for a significant reduction in lateral and backward shielding, and, as a result, a significant reduction in overall shielding weight can be achieved. The amount of weight reduction depends on factors such as the electron beam energy, the geometrical configuration of accelerator components and the shielding material used, but is on the order of several hundred pounds at a minimum for electron beam energies of 5 MV and above.

In some embodiments, the present specification provides an X-ray source design having significant weight reduction and performance improvement. In an embodiment, the X-ray source sub-system and methods of the present specification are used in mobile cargo inspection systems. In other embodiments, the X-ray source system and methods are used in any radiological application, where reduced shielding and lower weight is desired. As is known to those of ordinary skill in the art, X-rays produced by directing a 5 MeV to 10 MeV electron beam on a low-Z target have a steeper angular distribution in the forward direction than the X-rays produced from traditional high-Z targets like tungsten. In an embodiment, the system of the present specification compensates for the steeper angular distribution by use of magnetic beam transport and shaping of the low-Z target, thereby producing a more uniform coverage of the object being scanned than conventional systems with respect to both x-ray intensity and x-ray energy. Since the resultant X-ray beam has less intensity in the lateral directions, there is significant reduction in the shielding requirements leading to lower weight of the X-ray source.

In other embodiments, the system of the present specification employs a pulsed magnetic field in conjunction with a low-Z target, such that the central point of the forward focused X-ray beam is focused on areas of high density in the scanned object in an intermittent manner.

In other embodiments, the system also employs intensity modulation of the electron beam along with a pulsed magnetic field to ensure that all areas of the scanned object are illuminated with adequate/threshold intensity. In an embodiment, the system of the present specification continuously predicts the area of high density in the scanned object and re-focuses the central point of the forward focused X-ray beam towards the predicted areas of high density at each subsequent pulse. The total radiation intensity and hence the shielding requirement are significantly reduced in the above embodiment.

The present specification is directed towards multiple embodiments. The following disclosure is provided in order to enable a person having ordinary skill in the art to practice the invention. Language used in this specification should not be interpreted as a general disavowal of any one specific embodiment or used to limit the claims beyond the meaning of the terms used therein. The general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Also, the terminology and phraseology used is for the purpose of describing exemplary embodiments and should not be considered limiting. Thus, the present invention is to be accorded the widest scope encompassing numerous alternatives, modifications and equivalents consistent with the principles and features disclosed. For purpose of clarity, details relating to technical material that is known in the technical fields related to the invention have not been described in detail so as not to unnecessarily obscure the present invention. In the description and claims of the application, each of the words “comprise” “include” and “have”, and forms thereof, are not necessarily limited to members in a list with which the words may be associated.

It should be noted herein that image data is processed by a processing unit comprising a processor and memory to generate images of the cargo, which can be viewed on operator consoles. In accordance with the present invention, processing unit may be a general purpose computing device comprising various types of operating systems, memory configurations and computing platforms, as would be appreciated by a person of skill in the art. In one embodiment, data representative of the radiographic image is loaded from a memory device, which may include RAM, ROM, RAID array, flash drive, USB device, hard disk or other memory, to a processor that subjects the data to a program which includes instructions for performing image processing functions. In addition, those of ordinary skill in the art will recognize that devices of a less general purpose nature, such as hardwired devices, field programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), or the like, may also be used for processing the images without departing from the scope and spirit of the inventive concepts disclosed herein.

In addition, one of ordinary skill in the art would appreciate that the features described in the present application can operate on any computing platform including, but not limited to: a laptop or tablet computer; personal computer; personal data assistant; cell phone; server; embedded processor; digital signal processor (DSP) chip or specialized imaging device capable of executing programmatic instructions or code.

It should further be appreciated that the platform provides the functions described in the present application by executing a plurality of programmatic instructions, which are stored in one or more non-volatile memories, using one or more processors and presents and/or receives data through transceivers in data communication with one or more wired or wireless networks.

It should further be appreciated that each device may have wireless and wired receivers and transmitters capable of sending and transmitting data, at least one processor capable of processing programmatic instructions, memory capable of storing programmatic instructions, and software comprised of a plurality of programmatic instructions for performing the processes described herein. Additionally, the programmatic code can be compiled (either pre-compiled or compiled “just-in-time”) into a single application executing on a single computer, or distributed among several different computers operating locally or remotely to each other.

FIG. **1** illustrates a side view of an exemplary mobile inspection system of the present specification, in a deployed configuration. The system comprises a vehicle **101**, such as a truck, with a flat-bed surface and equipment mounted on it. The equipment, in one embodiment, comprises an X-ray source **102**, a boom **103**, a modulator **104**, a temperature control unit such as a chiller **105** and hydraulics assembly **106**. A radiation detector **107** is also mounted on the bed of the truck **101**. The front part of the vehicle **101** comprises the operator cab **108**. In an embodiment, the operator cab **108** has two or three operator stations, each equipped with large sized high-resolution displays for scanning operations. In an embodiment, the X-ray source **102** and the boom **103** are part of a single fixture that can be in either a deployed configuration or a stowed configuration. Making the source and the boom part of a single fixture ensures a rigid connection between the two, thereby minimizing alignment problems. In an embodiment, the boom **103** is foldable and is folded before storing it on the flat bed surface of the vehicle **101**.

FIG. **2** shows a close-up view of a mechanism **200** used to move the X-ray source and boom assembly **201**. In an embodiment, the mechanism **200** comprises a hydraulic system which in an embodiment is operated using a lever or a button. In an embodiment, the mechanism **200** comprises a first hydraulic piston **202** and a second hydraulic piston **203** wherein the first hydraulic piston **202** and the second hydraulic piston **203** are used to move the boom assembly in multiple directions. In an embodiment, the hydraulic system is capable of rotating the boom assembly horizontally by 5 degrees in either direction. This aids in scanning surfaces that would otherwise be parallel to the X-ray fan beam, such as the front and end of a container, or other perpendicular walls of a container.

Since the weight of the boom and source assembly may be considerable, in an embodiment, an outrigger wheel **301** is added to the system, as shown in FIG. **3**. This wheel is deployed before the boom is raised in order to improve system stability, and retracted after stowing the boom. In an embodiment, the outrigger wheel **301** is coupled to the vehicle **101** (shown in FIG. **1**) through a connecting part. The outrigger wheel **301** enhances stability of vehicle **101** and prevents it from tipping when the X-ray source and boom assembly are deployed, thus lending stability to the truck.

Further, as shown in FIG. **4**, in an embodiment, for a self-supporting boom structure, there are two sets of wheels **401**, **402** below the boom structure **403**. To avoid torsion of the boom structure **403**, wheels **402**, located on the distal end of the boom structure **403**, are powered by an electric motor, in an embodiment. These wheels can pivot, so that they will turn in the correct direction during deployment and retraction of the boom assembly. In an embodiment, the boom structure is designed to be wide enough to accommodate an imaging detector array and a neutron-based scanning system (not shown in FIG. **4**). Further, a wide boom improves rigidity to resist boom sway, which is important for reducing image artifacts, scatter and the size of the exclusion zone.

In an embodiment, the boom structure **403** approximates an inverse U shaped structure comprising a first vertical section **404** and a second vertical section **405** which are connected through a horizontal section **406**. In an embodiment, the truck **400** is connected to the first vertical section **404** at a position near its proximal end. The distal end of the first vertical section **404** is connected to the proximal end of horizontal section **406**. As described in the above embodiment, the vertical section **404** is also coupled to a wheel **401** at its proximal end which assists in the movement of boom structure **403**. In an embodiment, the proximal end of second vertical section **405** is connected to the distal end of horizontal section **406** and the distal end of second vertical section **405** is coupled to the wheel **402**. While in the above embodiment, the truck **400** is shown connected to the vertical section **404** at a position closer to the proximal end of the vertical section **404**, one of ordinary skill in the art would appreciate that the connection between truck and the vertical section **404** can be located at various other positions without compromising on the stability of system. In an embodiment, the two vertical sections **404** and **405** are substantially parallel to each other and are coupled to the horizontal section **406** in a perpendicular direction.

In an embodiment, the two vertical sections **404** and **405** are connected to the horizontal section **406** through a hinge **407** shown in the embodiment. In an embodiment, an X-ray source **102** (shown in FIG. **1**) is located substantially parallel to the two vertical sections **404** and **405**. In an embodiment, an outrigger wheel **301** (shown in FIG. **3**) is deployed before deploying the X-ray source to prevents the truck **400** from tipping as the weight of boom assembly and X-ray source may be substantial compared to the weight of truck. In another embodiment comprising a boom assembly with wheels that provide the support to the entire structure as described in the above embodiment, the outrigger wheel **301** is deployed just before deploying the boom assembly **403** and is subsequently retracted once the boom assembly is properly deployed.

In an embodiment, the X-ray source is vertically mounted as shown in the FIG. **4**, however, it can also be mounted and/or deployed in other configurations.

In an embodiment, the boom structure **403** is foldable such that it can be easily stored on the truck **400**. In an embodiment, the horizontal section **406** of boom structure **403** can be folded in two sub sections around the point **408** located on the horizontal section **406**. In another embodiment, the vertical sections are also foldable into two or more subsections to make the process of storage of the boom structure easy and convenient.

FIGS. **5***a* through **5***f* illustrate an exemplary stowing sequence for the boom structure. Referring to FIG. **5***a*, the horizontal section **501** of the boom assembly **500** is bent at middle point **502** towards the direction of the X-ray source and vertical section **503** of the boom assembly **500**. Next, as shown in FIG. **5***b*, if wheels are employed, the wheels **509** on the vertical section **504** orient themselves (automatically) toward the X-ray source **505**, and stay on the ground providing support until the source-side horizontal sub section **507** of the horizontal section **501** is fully vertical. Then the array-side horizontal sub section **508** of the horizontal section **501** is lifted up into the vertical position, such that the two vertical sections **503** and **504** move closer to each other as shown in FIG. **5***c* Next as shown in FIG. **5***d*, the entire source-boom structure **500** pivots around the assembly mount **510** towards the bed of the truck **511**, until as shown in FIG. **5***e*, the boom structure **500** is completely horizontal. The boom structure **500** is then pulled further into the truck **511** as shown in FIG. **5***f* using a suitable fixture (not shown in the drawings). The outrigger wheel **512** is also subsequently retracted.

One of ordinary skill in the art would appreciate that the reverse sequence is followed when the boom is deployed. In an embodiment, the boom structure is made up of a lightweight but stiff internal frame with plastic, carbon-fiber or thin aluminum covers.

FIG. **6** illustrates a mobile inspection system **601** as described in the present specification in scanning mode. A person of ordinary skill in the art would appreciate that the system is capable of scanning large trucks, such as the one **602** shown in the figure, as well as smaller vehicles. As a vehicle **602** passes through the portal **603** created by the boom, it is scanned using radiation from the X-ray source, as described throughout this specification. X-rays transmitted through (and attenuated by) the vehicle are detected by suitable detectors as described throughout this specification. In an embodiment, the detectors are integrated within the portions of the boom **604** that are opposite to the X-ray source and in the beam path. An image is generated from the detected radiation and it forms the basis of material discrimination. Further details of X-ray scanning systems are provided in U.S. patent application Ser. No. 13/577,170, which is herein incorporated by reference in its entirety. In an embodiment, the mobile inspection system **601** remains stationary while the vehicle **602** passes through the portal **604** coupled to the mobile inspection system **601**. In other embodiment, the vehicle **602** remains stationary and the mobile inspection system **601** moves past the vehicle **602** such that the portal **604** passes over the vehicle **604** to scan the same.

Reduced Overall System Weight and Size

Although the present system is designed to scan large containers and trucks, in an embodiment, the system itself is light-weight compared to existing mobile inspection systems and hence easy and flexible in deployment. In an embodiment, the reduction in overall system weight and size is achieved by using a weight optimized Diesel-Electric Hybrid Vehicle design. The hybrid vehicle uses a diesel/electric hybrid drive train which allows for about 25% reduction in system weight. This reduction in weight is achieved by optimizing the chassis chosen, supplementing system power demands with an electric motor while reducing the size of the diesel motor, in an embodiment. Additionally, in an embodiment, the heavy diesel generator usually used for operating the system in scanning mode is eliminated, and electric power is drawn from the main truck engine as part of its diesel-electric hybrid design. In existing systems, the operator stations which are used to analyze the scanning results are generally in a separate enclosure over the superstructure on the trunk bed of the inspection system. In an embodiment of the present specification, additional weight reduction is achieved by eliminating the separate custom operator enclosure, and integrating operator stations into inspection vehicle itself (as shown in FIG. **1**). Significant weight reduction is further achieved using custom-designed X-ray source shielding that is optimized for a particular radiation exclusion zone.

Cargo inspection systems typically use a linear accelerator X-ray source which produces X-rays not only in the desired direction (namely onto the object being scanned) but in all directions. These X-rays emanating in undesired directions are blocked by shielding. Typically, X-ray sources are specified to have a fixed fraction of "leakage" of X-ray energy in all directions except the desired direction, thus, a source is selected with a specified leakage level so that it complies with exclusion zone requirements. The exclusion zone is usually defined as a rectangular area, chosen such that the radiation at the boundary of the area does not exceed a certain maximum dose rate, averaged over the course of one hour. Calculations and measurements, however, show that the customer-specified exclusion zone, as well as the actual inspection system geometry, has various asymmetries that lead to an exclusion zone that is better than required in some directions, which can mean that either the exclusion zone could have been smaller in some directions, or that there is too much shielding present in those directions. The shielding could, in principle, be removed without affecting the performance of the system. Since the shielding consists of lead and tungsten, significant weight reduction can be achieved using an optimized shielding design.

Thus, in an embodiment, the present specification optimizes the weight of the shielding to obtain an overall X-ray source weight of about 4000 pounds for a 6 MV source. This is significantly lower compared to the weight of a standard 6 MV source, which, for the ultra-low-leakage version (10^{-6} leakage fraction), is about 7800 lbs.

FIG. **30** illustrates an exemplary calculated shielding boundary, in inches, where shielding thickness in all directions is optimized for a particular maximum dose at a particular predetermined boundary. The x-axis represents the "lateral" direction, or the scan direction. The y-axis represents the horizontal direction of the x-ray beam. Referring to FIG. **30**, curve **3101** shows the total shielding outline. Line **3102** represents the extended target, which, in an embodiment, is a target that is located beyond the end of the linear accelerator, usually at the end of a narrow tube that extends in front of the linac. In one embodiment, an extended target is employed to enable easier shielding of the immediate surroundings of the target, since the tube is narrower than the linac. Line **3103** represents an outline of the tungsten shield. Stepped lines **3104** and **3105** represent right-hand and left-hand shielding designs, respectively, which can be arrived at when using plain lead cylindrical sections. In one embodiment, extra shielding is provided in the direction of the operator location, as indicated by the asymmetrical lateral deviation in line **3105** between y=−5 and y=5 inches, as compared to line **3104**. For a system with only a forward directed beam, the shielding is, in one embodiment, approximately cylindrically symmetric, with the exception of lateral deviation.

In other embodiments, where electron beam steering is employed, as described below, the shielding can be positioned more closely in the lateral or horizontal direction, but not vertical, since the electron beam needs room to deflect and come in from different angles. Thus, the shielding in the vertical direction, in these cases, is farther from the source. FIGS. **31***a* and **31***b* show the left and right sides of a possible shielding implementation, respectively corresponding to the exemplary shielding pattern described in FIG. **30**. Referring to FIGS. **31***a* and **31***b*, a vertically mounted source **3201** is equipped with shielding designed to contain both tungsten **3202** as well as lead **3203**. Further, additional operator shielding **3204** is also provided. Further details of a vertically mounted source are provided in the following sections, with reference to FIG. **16**.

Systems and methods of reducing X-ray source shielding requirements, thereby reducing the overall weight of a linear accelerator X-ray source, are described in further detail in U.S. Provisional Patent Application No. 61/761,690 and in U.S. Provisional patent application Ser. No. 13/492,614, both of which are herein incorporated by reference in their entirety.

Reduced Radiation Exclusion Zone Through Vertical Intensity Modulation

Modulation of X-rays in the vertical plane helps to reduce the size of exclusion zone and specifically target regions of high attenuation in a focused manner. Vertical intensity modulation of X-rays can be achieved through multiple methods. The present specification describes methods and systems for implementing vertical intensity modulation.

FIG. **35***a* illustrates a system for vertical intensity modulation in a single-energy system which employs a quadrupole magnet, and specifically a DC quadrupole magnet, in accordance with an embodiment of the present specification. As shown in FIG. **35***a*, a pulsed dipole steering magnet **3602** changes the direction of single-energy electron beam **3600** such that electron beam **3600** passes through a magnetic field created by employing a DC quadrupole magnet **3603**. In an embodiment, the magnetic field generated by using DC quadrupole magnet **3603** is configured such that it deflects the direction of single energy electron beam **3600** which then strikes the target **3604** at a specific point at a desired angle. The exact angle at which electron beam **3600** strikes the target **3604** determines the direction in which the generated X-ray beam has maximum intensity.

In an embodiment, the system analyses the image slice recorded in each pulse to determine the areas of high attenuation in the scanned object. Subsequently, in the next pulse, the quadrupole magnet **3603** changes the direction of electron beam **3600** such that the electron beam **3600** strikes the target **3604** at an angle which generates X-rays focused towards the area of high attenuation captured in the previous pulse. In one embodiment, the electron beam is adjusted continuously between successive X-ray pulses.

In some embodiments of the present specification, the system employs dual-energy beams for material discrimination instead of the single-energy methodology described above. In the case of a dual-energy beam, vertical modulation of the electron beam is more complicated. For dual-energy beams, the magnetic field is configured such that two consecutive beams of different energies have the same trajectory, which is switched at each pulse depending on the cargo attenuation requirements. The magnetic field strength needed to deflect a low-energy electron beam is lower than the field strength needed to deflect a higher-energy electron beam. In an embodiment, the present specification employs one or more shaped magnetic fields such that the electron beams passing through such shaped magnetic fields arrives at the target at the same location regardless of the energy of the beam. In an embodiment, to cause both the high energy and the low energy electron beams go through the same trajectory, the magnetic field is switched between two different field strengths. In an embodiment, the X-ray source uses a pulsed quadrupole magnet to provide the required magnetic field. As is known to those of ordinary skill in the art, a pulsed quadrupole magnet is one that switches between two different field strengths, to compensate for the difference in energy of the electron beam between one pulse and the next. It should be noted that in the case of dual energy, the two beams of different energies arrive in successive, and not simultaneous, pulses. Thus, a first energy will arrive in a first pulse while a second energy will arrive in a second pulse. This "switching" between energies remains consecutive, with the first energy arriving in the third pulse and so forth.

FIG. **35***b* illustrates vertical intensity modulation in a dual-energy system which employs a pulsed quadrupole magnet in accordance with an embodiment of the present specification. As shown in FIG. **35***b*, pulsed dipole steering magnet **3602** changes the direction of dual-energy electron beam **3601** such that the dual-energy electron beam **3601** passes through a magnetic field created by a pulsed quadrupole magnet **3605**. In an embodiment, the pulse strength of the pulsed dipole magnet **3602** is adjusted such that the magnetic field applied to the electron beam in the dipole magnet positions the electron beam into the desired trajectory through the quadrupole magnet **3605**. In an embodiment, the magnetic field generated by using the pulsed quadrupole magnet **3605** is configured such that it deflects the direction of dual energy electron beam **3601** which then strikes the target **3604** on a specific point at a desired angle. The exact angle at which dual energy electron beam **3601** strikes the target **3604** determines the direction in which the generated X-rays beam has maximum intensity. In an embodiment, the pulsed quadrupole magnet **3605** is pulsed to adjust the magnetic field for deflecting the two energies appropriately. In one embodiment, the target is made of a high-Z material, such as tungsten, as is used in conventional x-ray sources. In another embodiment, the target is made of a low-Z material, which tends to make the x-ray beam intensity more forward-focused.

FIG. **35***c* illustrates the system for beam steering in a dual energy system which employs two DC quadrupole magnets in accordance with an embodiment of the present specification. As shown in FIG. **35***c*, dual energy electron beam **3601** deflected by the steering magnet **3602** is transported through a magnetic field created by two DC quadrupole magnets **3606** which steer the electron beams such that the two beams of different energies have the same trajectory which is switched at each pulse depending on the cargo attenuation requirements.

In an embodiment, a first vertical slice of the cargo image is acquired by pulsing the X-ray source and acquiring data from the detector array. This slice is analyzed, and the signals from the detector array are used to estimate the area within the cargo in which the intensity is the highest, and from that the optimal electron beam angle and instantaneous beam current are determined in order to adequately image the cargo while maintaining a low dose. In an embodiment, these settings are then applied to the next slice after which the process repeats until the entire cargo object is scanned. In one embodiment, the electron beam is adjusted continuously between successive X-ray pulses. Lower-attenuation areas of the cargo are scanned with progressively lower X-ray intensities, since these areas are further away in angle from the maximum level of emission.

Reduced Radiation Exclusion Zone Through Electron Beam Steering

In an embodiment of the present specification, a smaller exclusion zone and hence lower weight of the X-ray source is accomplished using enhanced beam collimation achieved through electron beam steering. In an embodiment, the electron beam in an X-ray generator tube is directed onto a custom target in a manner that produces “forward radiation” at a number of different angles, thereby making it possible to achieve better angular coverage and only in the desired directions.

In an embodiment, the electron beam emerging from the linear accelerator in the X-ray source is defocused to split it into multiple portions which are then transported with the help of a shaped magnetic field to strike a shaped target at multiple angles. The target point itself does not move, rather, parts of the electron beam arrive from different directions in the vertical plane. Since the X-rays are produced from the target with the highest intensity in the direction of the electron beam, a high dose is produced in multiple directions simultaneously, resulting in the cargo being scanned with an X-ray fan beam, that is more uniform in the vertical direction and that is collimated in the vertical plane. At certain x-ray intensities, a conventional non-uniform beam would not provide sufficient intensity to adequately image parts of the cargo not covered by the highest intensity of the beam. Since the X-ray intensity in the fan beam is more uniformly spread across the cargo, the overall intensity of the electron beam can be reduced. Because of this overall reduction in X-ray intensity, the shielding, particularly in the lateral direction, can be reduced, leading to a lower overall source weight. In one embodiment, the target is made of a high-Z material, such as tungsten, as is used in conventional x-ray sources. In another embodiment, the target is made of a low-Z material, such as, but not limited to carbon, which tends to cause the x-ray beam intensity to be more forward-focused, which allows the lateral shielding to be further reduced, resulting in additional weight reduction of the X-ray source.

In an embodiment, the emission intensity angular profile is used to estimate whether a sufficient amount of X-ray intensity is used to adequately penetrate and image the cargo at all angles in the plane of the X-rays. In another embodiment, electron beam steering is combined with X-ray source intensity modulation. If it is determined that some areas require a higher intensity, in an embodiment, the overall intensity of the X-ray source is increased, as described in the paragraphs below.

In an embodiment, the present specification describes an X-ray source with a low-Z target which causes the X-ray beam to be more forward-peaked. In an embodiment, electron-beam steering is selectively applied to direct the forward-peaked X-rays towards areas in the cargo with high attenuation. In some embodiments, the low-Z target is shaped. In an embodiment, the shaped target has a semicircular shape. In other embodiment, the shaped target has a triangular shape. In an embodiment, the target has a flat shape.

In some embodiments, the low-Z target is carbon. In some embodiments, the low-Z target is graphite. In some embodiments, the low-Z target is formed from diamond, which exhibits good heat conduction properties, since the heat produced by the electron beam in the target needs to be adequately dissipated. Since X-rays generated from a low-Z target are forward-peaked, they allow for a significant reduction in lateral and backward shielding, and, as a result, a significant reduction in overall shielding weight can be achieved.

It should be noted herein that the material of the target may be selected depending upon the application of the present specification. For example, tungsten may be selected for a wide fan beam, low-Z materials such as graphite may be selected for a narrow fan bean, or copper may be selected to reduce the production of photo-neutrons.

FIG. **32** is a graph depicting the intensity of an x-ray source vs. the x-ray source angle corresponding to two similar x-ray sources coupled with a) a low-Z target and b) a high-Z target. FIG. **32** shows X-ray angular distributions **3302**, **3304** with respect to the electron beam direction in an X-ray inspection system, for two radiation sources, simulated using the EGS electron-photon transport code, and normalized to yield **1** in the forward direction (angle=0). EGS is a standard simulation code. It should be noted herein that other simulation codes would yield similar results. The sources simulated here are standard 9 MV sources in which electron beams strike a target. The energy of the source does affect the overall shape;

however, it does not affect the fact that a low-Z target has a steeper angular fall-off than a high-Z target. One of the sources in the simulation is coupled with a high-Z target, such as tungsten, which has an atomic number of 74 (Z=74), while the second source is coupled with a low-Z target, such as graphite, which has an atomic number of 6 (Z=6). During simulation internal tungsten shielding is provided in a backward direction. While X-ray intensity distributions obtained are averaged over all the x-ray energies, the angular distribution is steeper for the higher energy X-rays than for the lower energy X-rays. As is illustrated in FIG. **32**, at an angle **3306** of approximately 30 degrees (as shown on the x-axis), the intensity **3302** of the x-ray source coupled with the graphite target is lower than the intensity **3304** of the x-ray source coupled with the tungsten target by a factor of two. Thus, as illustrated, significant amounts of shielding material may be eliminated by using a low-Z target such as graphite instead of a high-Z target like tungsten in an x-ray inspection system. Since such shielding is usually in the form of lead, and since the shielding can be removed from the outer layers when a low-Z target is used, this adds up to a significant shielding volume and therefore weight. By way of an example estimate, it is calculated that at a minimum, a layer of one half inch (about one half-value layer) of lead at a radius of 25 cm with a weight of approximately 200 pounds can be omitted by using a low-Z target. In reality, typical shielding designs are much more complicated, in part because of the geometry of the linear accelerator components and in part because of the change of the energy spectrum with angle, and therefore a larger amount of excess shielding could most likely be removed. It should be noted that the example provided above is only for exemplary purposes and in no way limiting to the present specification.

High-Z targets provide a more uniform intensity of an x-ray fan beam which is typically used in cargo radiography systems, as compared to low-Z targets. In general, angular coverage is approximately a factor of two lower for a low-Z target than a high-Z target. Typically, angular coverage of an X-ray beam in a standard cargo radiography system is around 70 degrees (35 degrees in each direction as measured from where the beam exits the x-ray source) which is typically obtained by using a high-Z tungsten target. It should be noted that this coverage is still not very uniform, however. For example, at 35 degrees, the intensity is only 30% of the forward intensity (for a 9 MV source). When a low-Z target is employed, the equivalent angular coverage is approximately 34 degrees (17 degrees in either direction). Generally, angular coverage is even lower considering the energy spectrum of the x-rays at such angles; for example, lower-Z targets have a faster fall-off of high-energy x-rays, and thus have less coverage for the high energy x-rays which are more useful for radiography. On the other hand, however, this makes sources with low-Z targets easier to shield.

In an embodiment of the present specification, the electron beam in an x-ray generator tube is directed onto a custom target in a manner that produces "forward radiation" at a number of different angles, thereby making it possible to achieve better angular coverage than with a beam producing "forward radiation" in only one direction in the desired vertical plane. Forward radiation, or forward peaked radiation, is radiation that is preferentially emitted in the same direction as the electron beam direction when the latter strikes the target. More forward-peaked radiation is radiation that is concentrated in a smaller range of angles with respect to the electron beam direction. Referring to FIG. **32**, for a high-Z target (tungsten) the intensity of the radiation averaged over all energies drops to half of its 0-degree value at an angle of about 15 degrees. For the low-Z target (graphite), the intensity of the radiation drops off to half of its 0-degree value at about 9 degrees. Therefore, for a low-Z target, the intensity of the radiation drops off to half of its 0-degree value at a smaller angle range than for a high-Z target. Also, for a low Z target, the forward-peak nature of the emission is indicative of having at least 50 percent of the intensity of the total radiation concentrated in angles less than 10 degrees from the emission point. It should be appreciated that shielding can be decreased in areas beyond a particular angle, as measured from the emission point, where the intensity has sufficiently decreased, such as beyond 9, 10, 11, 12, 13, or 14 degrees, relative to the shielding between the particular angle and emission point.

It should be appreciated that a low-Z target is an electron beam target comprising materials with an atomic number, Z, which is less than that of iron, e.g. 26. A high-Z target is an electron beam target comprising materials with an atomic number, Z, above that of tin, e.g. 50. For example, carbon and its forms (such as graphite and diamond) have a Z of 6 while tungsten has a Z of 74.

In an embodiment, the system of the present specification compensates for the steeper angular distribution by use of magnetic beam transport and shaping of the low-Z target, thereby producing a more uniform coverage of the object being scanned than conventional systems with respect to both x-ray intensity and x-ray energy. In one embodiment, electron-beam steering is employed to direct the electron beam at the tip of the target from below or above at different angles, in order to direct the maximum of emission of these X-rays towards high-attenuation areas in the cargo, at various angles. In an embodiment, the electron beam is steered by use of a suitably designed magnet, or by electrostatic deflectors, or by a combination of both. In an embodiment, the X-rays are collimated into a fan beam.

In an embodiment, the magnetic elements comprise a defocusing magnet, such as, but not limited to, a quadrupole magnet. A defocusing magnet applies a magnetic field to an electron beam which causes portions of the electron beam to diverge from each other. Depending on the target configuration, those diverging portions may then impinge on different locations on the shaped target. For example, for a small shaped diamond target, the diverging beam is then refocused using an appropriately shaped magnetic field, such as a focusing quadrupole, or a combination of a focusing quadrupole and a steering dipole.

In an embodiment of the present specification, in an X-ray source having single energy electron beam, vertical intensity modulation can be achieved through electric or magnetic elements which change the direction of the electron beam **3702**, as shown in FIG. **36*a***, such that it arrives at the target **3701** at a different angle, directed towards a region of high attenuation in each pulse. FIG. **36*b*** shows an electron beam **3704** moving in a different path from its original direction **3706**, bending back towards the target **3703**, and arriving at target **3703** at an angle θ **3705**. In an embodiment, the magnetic elements used for vertical intensity modulation comprise a pulsed dipole magnet and a DC quadrupole magnet. In another embodiment, the elements used for vertical intensity modulation comprise a pulsed electrostatic deflector and a DC quadrupole. In yet another embodiment, multiple electric and magnetic deflection devices are used, some of which may or may not be DC or pulsed. In one embodiment, the target is made of a high-Z material, such as tungsten, as is used in conventional x-ray sources. In another embodiment, the target is made of a low-Z material, which tends to make the x-ray beam intensity more forward-focused.

FIG. 33 illustrates an x-ray fan beam generated by using a custom low-Z target, in accordance with an embodiment of the present specification in which the magnetic elements comprise a defocusing magnet. As shown in FIG. 33, in an embodiment, magnetic element 3430 comprises a defocusing quadrupole magnet. The transported beam 3440 enters a shaped magnetic field 3450, designed to transport different parts of the beam 3440 to different areas on a shaped target 3460 to produce x-ray fan beam 3470. The geometry is optimized in order to provide a reasonable virtual focal point 3461 for the produced x-rays 3470. Thus, in an embodiment, the shaped magnetic field is arranged to transport the electron beam or parts thereof onto the shaped target in such a way that the x-rays will all appear as if they come from within a short distance of a particular point within the target.

In an embodiment, the shaped magnetic field is created by optimally arranging magnetic materials and electric coils, as is known to those of ordinary skill in the art. The magnetic field and target geometry are optimized to make as small a beam spot as possible. Both geometries are preferably optimized. In this embodiment, the main characteristic is to make it appear as though the x-rays all come from the same spot.

In an embodiment, the x-rays produced are forward-peaked, thereby reducing the amount of lateral shielding because of the reduced intensity and energy of the x-rays emerging in lateral directions, thereby reducing the probability of freeing neutrons from the shielding material. These neutrons are a nuisance in that they can produce spurious signals in nearby detectors, and using this method reduces the occurrence of such spurious signals. Further, in using the method of the present specification, the thickness of materials, type of materials, and geometries needed to shield against these neutrons can be altered and/or reduced.

In another embodiment, the magnetic elements comprise a bending magnet which can be set to bend the electron beam towards at least one of a plurality of areas within a shaped magnetic field that in turn transports the electron beam onto a corresponding plurality of parts of the shaped target, arriving there in a corresponding plurality of particular directions optimized for producing x-rays in the desired directions. In an embodiment, the bending magnet is set to bend the electron beam towards one of said plurality of areas within the shaped magnetic field on each subsequent accelerator pulse, in a sequence that comprises each of said plurality of areas. Between pulses the bending magnet field strength is adjusted appropriately in order for the beam to be directed towards the next area of the shaped magnetic field in the sequence, as desired.

FIG. 34 illustrates an x-ray fan beam generated by using a low-Z target, in accordance with an embodiment of the present specification, in which the magnetic elements comprise a bending magnet. As shown in FIG. 34, electron beam 3510, after passing through accelerator 3520, is transported in a vertical direction by using magnetic elements 3530. In an embodiment, magnetic elements 3530 comprise a bending magnet that is set to bend the electron beam on each subsequent accelerator pulse, thus creating a switching magnetic field. The transported beam 3540 enters a shaped magnetic field 3550, designed to transport different parts of the beam 3540 to different areas on a shaped target 3560 to produce X-ray fan beam 3570. The x-rays from different pulses of the x-ray source are transported by the shaped magnetic field 3550 to different areas on the shaped target 3560, such that the x-rays appear as if they come from different points (x-ray spots) 3561 within the target. Therefore, the electron beam in an X-ray generator is switched from one direction on a target to another in successive electron pulses, in order to generate X-rays having a uniform intensity.

By transporting the x-rays from different pulses of the x-ray source by the shaped magnetic field to different areas on the target, such that the x-rays appear as if they come from different points within the target, a plurality of separate images can be produced, each from a separate vantage point. In the case where the system is applied in a radiography configuration, the separate images can then be used to obtain 3D information about the object being scanned, as is known to those skilled in the art.

Reduced Radiation Exclusion Zone Using Intensity Modulated Advanced X-Ray Source

It should be evident to those of ordinary skill in the art that in many situations, only a limited amount of space is available to perform cargo scanning operations. At some ports of entry and in urban environments, the space is particularly limited. To that end, the scanning system of the present specification aims to provide the same imaging performance using a smaller footprint, thereby increasing its operational effectiveness. This is done, in an embodiment, by reducing the size of the exclusion zone and keeping the dose rate low, without compromising on the image quality.

In an embodiment, the exclusion zone is less than 36 m (120 ft) in the scan direction and less than 20 m (66 ft) perpendicular to the scan direction when scanning cargo equally divided between low-, medium-, and high-density cargos. At the same time, the dose to the driver and inspectors is less than 100 mrem per year, while the dose to cargo and possible stowaway is less than 0.5 rad (5 mSv) per scan at the cargo container/vehicle surface nearest to the radiation source.

In order to reduce the exclusion zone in the perpendicular direction, the present system employs an advanced intensity modulated X-ray source technology. In general, the higher the source intensity at a given source energy, the greater the amount of material the X-ray beam can penetrate and the better the contrast resolution. In current practice, the X-ray source intensity of an inspection system is set to the highest level allowable under the particular circumstances of the system and the inspection area, and all cargo is inspected using this fixed intensity, whether the accurate inspection of the cargo requires this intensity or not. The inspection intensity, however, is typically not the highest rated intensity that the source is capable of producing and is often set to not exceed a specified radiation dose limit at the boundary of a predefined Exclusion Zone. An intensity-modulated source changes intensity based on the results of the current X-ray pulse and uses a higher or lower intensity for the next X-ray pulse, if possible. That is, for each slice of the image, the current slice is analyzed and then source settings for the next pulse are optimized. In an embodiment, optimized settings include source intensity, energy and/or pulse frequency, detector integration time, and collimator settings. Use of an intensity modulated source can also involve adaptive image processing, both in the temporal and the spatial domain. In an embodiment, the system uses pulse-width modulation to change X-ray intensity. In another embodiment, pulse-height modulation is employed for intensity modulation by changing the instantaneous electron beam current. As will be recognized by those skilled in the art, pulse-height modulation is preferred for the purposes of X-ray spectroscopy, since the X rays arriving in a detector are spread out over the longest possible pulse duration.

Systems and methods for using an intensity-modulated X-ray source are described U.S. Pat. Nos. 8,781,067, 8,437,448 and 8,054,937, all of which are incorporated herein by reference in their entirety.

In an embodiment shown in FIG. **29**, a cylindrical filter **3000** is shown which is inserted into the path of X-ray beam to regulate the intensity of X-rays in different directions. In an embodiment, the cylindrical filter **3000** comprises a slot **3002**, which in an embodiment is configured in an approximately "spiral" shape and runs along part of the circumference of the cylindrical filter **3000**. Multiple planar images **3001** of the cylindrical filter **3000** illustrate the shape and position of twisted slot **3002** when cylindrical filter **3000** is viewed from different directions. The filter **3000** helps to reduce the exclusion zone by using a mechanical means to achieve vertical beam intensity steering. In an embodiment, as the cylindrical filter **3000** rotates, the X-rays passing in different vertical directions through the slot **3002** are controlled leading to lower radiations emanating in undesired directions and a reduced exclusion zone. In some embodiments, the filter allows for attenuation of X-rays in some directions and allows for the full beam of X-rays to pass through in other directions. In other embodiment, small individual filter sections are inserted into the fan beam by means of actuators.

Improved Image Quality Using Gapless Detector Array

In some embodiments, the present specification significantly improves image quality and aims to reduce image artifacts for better identification of threats and contraband. It is well known in the art that artifacts, such as "hot line" and "fade artifact" are mainly produced by the scatter of the X-ray beam by the cargo, the detector array, boom structure, and associated structures. Further, "curtain artifact" is generated by boom oscillations at a number of frequencies that are predicted to occur as a result of resonances arising from the boom structure. The magnitude of the curtain artifact is determined by the width of the fan-beam, how well the fan-beam is aligned with the detector array, the magnitude of the boom motions, and the method used to normalize intensity variations from the linac.

In an embodiment, the system of the present specification counters scatter-related artifacts by at least one of the following:

1. reducing the width of the X-ray fan beam;
2. designing the X-ray detector array to remove sources of scatter; and
3. improving detector collimation.

Reducing scatter reduces the magnitude of the fade artifacts, and also helps to preserve the exponential relationship between the transmittance of the X-ray beam and the thickness of the object. This further helps the segmentation and classification of anomalous regions in the image. It may be noted that decreasing the width of the X-ray beam may cause the magnitude of the curtain artifact to increase. To counter that, the present specification implements several improvements to the boom structure employed in mobile applications to make it stiffer to dampen the vibrations, or shift to the natural frequencies.

Further, the system of the present specification improves the minimum observable contrast by using lower-noise detector electronics to achieve a reduction in the dark noise.

In an effort to eliminate the artifacts and to improve the situation with regard to X-ray scatter into the detectors, in an embodiment, the present system employs a collimated detector array design that has essentially no gaps, and where the collimator can be integrated into the boom design as a support element, reducing its effect on boom weight.

Because the source is a virtual point some distance away from the detector array, the only way to mount the modules in a way that leaves (mostly) no gaps is in a circular arc. This is, however, not usually feasible, since it takes up too much space. Thus, it may be noted that cargo inspection systems typically use an inverted-L-shaped detector array, as shown in FIG. **7**. The L-shaped array **701** is preferred (over a circular arc) because it is spatially the most efficient layout, considering the rectangular cross section of a cargo container and the fan-like geometry **702** of a collimated X-ray beam, provided by the source **703**. For high-energy X-ray inspection, the detectors in the detector array are narrow/thin for better spatial resolution and long in order to efficiently capture the transmitted X-rays. Because of this, the detectors need to be aimed more or less towards the source of the X-rays, or else the X-rays from the source would cross multiple detectors, reducing or eliminating the high spatial resolution.

Therefore, it is common practice to design the detector array such that it consists of a number of detector modules, each of which comprises several detectors, and each of which is mounted at a different angle in the array, optimized so that each detector in the module more or less is aimed at the source. The only way to mount the modules in this fashion is by offsetting one module from another, each one mounted at a slightly different angle, as shown in FIG. **8**. FIG. **8** shows a typically configured detector array in which linear sections are "forced" to point to the source in a straight array. These discontinuities or "gaps" then lead to what is known as the horizontal line artifact. While this artifact can, to some degree, be addressed in software, it would be preferable to have a detector array design that would not exhibit this problem in the first place. FIG. **9** shows an ideal configuration of such detector, however, requires that each of the many detector elements (on the order of 1200 or so) to be aligned individually to aim at the source. This would require different electronics boards/mounting structures for each element.

FIG. **10** illustrates an exemplary layout, where each "detector" is individually aligned to aim at the source. The "detector" described in this embodiment comprises multiple smaller detector segments. Referring to FIG. **10**, instead of a one-dimensional single array composed of modules with multiple long, thin detectors, the present specification uses a two-dimensional array **1001** of small detector segments **1003** (segmented detector array), with both dimensions in the plane of the fan beam **1002**. The detector array **1001** comprises small detector elements **1003** and each detector element comprises a scintillator **1004**. Thus, at each location in the detector array, a set of detector elements **1003** can be found such that the set as a whole is aligned towards the X-ray source **1006**. Each detector element **1003** is also outfitted with a small photo-detector **1005**, to read out the scintillator crystal.

As mentioned earlier, traditional detector arrays for high-energy X-ray systems have fairly long detectors in order to be able to detect the X-rays with good efficiency. For such scintillators, a length of 20-30 mm is usually sufficient. In the present specification, in an embodiment, the long crystal is replaced with a "virtual detector" consisting of about 6 crystals of size 5×5×5 mm. The six small crystals in this example have the same total volume as one long crystal, and therefore overall X-ray detection efficiency will be the same, if the signals from the separate crystal segments are added together. Total scintillator cost would also be very similar, and the yield of small crystals is usually higher than that of larger crystals.

FIG. **11** illustrates how X-rays **1101** coming from the source intersect the array at different angles **1102**. It should be noted in the figure that the darker shaded sets of detector elements show exemplary sets of detector elements that aim back at the source at various angles. For any given angle of incidence, a "virtual detector" consisting of a certain combination of detector segments is representative of the signal in that direction. Thus, different combinations of small detector segments form the virtual detector for each different point of incidence and X-ray direction. Such an array can be constructed in the form of modules that are mounted in the inverted L-shaped housing while leaving no gaps, thereby eliminating the horizontal line artifact. In addition, this depth segmentation reduces the X-ray count rate in any given detector segment compared to the original case, making it easier to implement spectroscopic algorithms. Moreover, the deeper detector segments see a filtered signal, where the filter is provided by the upstream detector segments. This improves the results of spectroscopic algorithms.

In an embodiment, different scintillator materials are used for the different segments, so as to have different average Z. Dual-detector operation can simply be implemented by combining the signals from some front detector segments and from some rear detector segments. Further, it is in principle possible to exploit the segmentation to improve the spatial resolution.

FIG. **12** shows a graphical comparison of light collection efficiency for small detectors **1201** with that of large detectors **1202**, as a function of photodiode size. The detector crystals are assumed to be painted with white paint. It is clear from the figure that the light collection efficiency for a long thin detector with a paint reflector is rather low, and in addition it is non-uniform over the length of the crystal. On the other hand, smaller crystals have much improved light yield, and much better light collection uniformity, even with a much smaller photodiode.

In another embodiment, a detector array comprises a number of long thin detectors. It should be noted herein that the description below applies to a detector array comprised of long, thin detectors due to spatial considerations. Specifically, the previously described implementation (segmented detector array) needs room for the side-mounted photo-detector and electronic circuit board. In addition, for a segmented detector array, one would need additional room on at least one side of the collimator. A possible implementation is illustrated in FIG. **22**, and comprises an array of 16 scintillator crystals **2301** with photo-detectors. In an embodiment, the scintillator crystals can be manufactured from materials such as LYSO or cadmium tungstate or lead tungstate or any other kind of scintillating materials.

In some embodiments, the photodetectors may be photodiodes, biased photodiodes for implementation of noise spectroscopy, avalanche photodiodes, or silicon photomultipliers (also known as multi-pixel photon counters) for implementation of transmission Z-spectroscopy. In some embodiments of the present specification, scintillator crystals and their associated photo-detectors can be replaced by solid state detectors made from a semiconductor material, such as, but not limited to, Cadmium-Zinc-Telluride (CZT). In another embodiment, the scintillator crystals can be replaced by a cerenkov detector.

Since, in an embodiment, the angle, and therefore the spacing, of the vertically stacked detectors changes every 64 detectors, in an embodiment, the present specification uses a dual-circuit-board approach to the read-out, shown in FIG. **23**. A small, elongated board **2402**, called the detector interface board (DIB) serves as a way to gather the signals from all the photo-detectors onto an edge-connector **2403**. In an embodiment, there are 18 versions of this detector interface board (DIB), each occurring 4 times per system, and each with slightly different spacing of the photo-detector connections.

In an embodiment shown in FIG. **24**, a second board **2504**, which is the data acquisition board, plugs directly into the edge connector **2505**. In an embodiment, the data acquisition board (DAB) serves 16 channels of detectors, and is identical across the entire detector array.

In an embodiment, the scintillator crystals are polished on all sides, or have a ground surface. They need a reflector, but the current practice of painting the crystals cannot be used where noise spectroscopy or transmission Z-spectroscopy techniques are to be implemented, since in order to ensure uniform light collection in these methodologies, there has to be an air gap between the crystal and the reflector. An additional consideration is that the reflector material should be fairly opaque, in order to avoid cross talk between neighboring detectors. Therefore, in an embodiment, an extrudate is made from opaque or relatively opaque, highly reflective material.

An extrudate is shown as **2610** in FIG. **25***a*. In an embodiment, the extrudate has room for 16 detectors, with 1 mm of reflecting material between detectors, and 0.5 mm at the edges, so that two neighboring detectors in two adjoining modules also have 1 mm of reflecting material between them. Further, individual reflector assemblies can then be made for each detector module by cutting through the extrusion at the appropriate angle. For example, as shown in FIG. **25***b*, the extrudate from FIG. **25***a* can be cut at various angles to make detector housings **2620** and **2630**.

In another embodiment, a custom part is machined from opaque or relatively opaque, highly reflective material such as Labsphere Spectralon. Thus, in cases where the reflector material cannot be subject to an extrusion process, detector housings **2620** and **2630** can be machined, and can consist of one machined part, or from more than one machined part and glued together, using common machining and adhesive techniques.

FIGS. **26***a*, **26***b* and **26***c* illustrate a detector assembly with a reflector and a detector interface board (DIB). The LYSO detectors **2701** are inserted into the reflector **2702** made for the particular detector module, which serves as a detector housing. In an embodiment, the holes on either end are plugged with some moldable white reflector material, such as plaster of Paris, or white putty. In another embodiment, the plug is made from the same reflector material that is used for the rest of the detector housing, either as an integral part of the detector housing, or as a separate part that slides into the opening. In an embodiment, one plug has holes in it to enable the leads for the photodetector to pass through. In another embodiment, a combination of materials is used. In an embodiment, the leads **2704** are soldered into a DIB **2703** of the appropriate size, as shown in FIG. **26***b*. The final detector module is shown in FIG. **26***c*.

FIG. **27***a* shows the detector array assembly **2810**, comprising a data acquisition board (DAB) **2820** for every 16 channels of detectors. In an embodiment, the angle with which the detector assemblies are constructed is not kept uniform along the entire length of detector array to ensure that the detectors are properly aligned in the direction of X-ray source. In FIG. **27***a*, in an embodiment, the angle **2825** is changed after the fourth DAB.

In an embodiment, the detector module is inserted into a collimator such as the collimator **2830** shown in FIG. **27***b*. In an embodiment, the collimator is made of steel. FIG. **27***c* illustrates a detector assembly inserted into a collimator. Referring to FIG. **27***c*, a detector assembly **2850** is inserted into a steel collimator **2852**. Steel is chosen because it is less dense than lead and is structurally superior. Therefore, the collimator can be made a part of the structural form of the detector boom, thereby fulfilling two roles at once. This is shown in FIG. **13**, wherein the detector-collimator assemblies **1401** are integrated within the boom **1402**. While lead is preferred because it has better attenuation, only a fairly shallow collimator made of lead can be allowed due to weight considerations. A shallow collimator, however, has a larger opening angle and will allow more scattered radiation to reach the detectors. To make up for the lack of density, a steel collimator can be made with the same attenuation but with more depth. In an embodiment, the steel collimator is about 4 inches deep, with a gap of exactly the width of the detectors, which is 5 mm in the present example. In order to keep this spacing constant throughout the array and for stability, in other embodiment the collimator is welded to a square tube of appropriate size and strength. In another embodiment, a thin steel cover on the end of the collimator opposite the detectors is used.

FIG. **28** shows a cross sectional view of the detector assemblies inserted into the steel collimator **2910**, with a part of the collimator not drawn to enable seeing the detector housings inside. As can be seen from the figure, the collimator **2910** is placed over the detector housing and reflector **2920**, which couples the array to the detector interface boards (DIB) **2930** and the digitizer boards **2940**. In an embodiment, the angle with which the detector assemblies are constructed is not kept uniform along the entire length of detector array to ensure that the detectors are properly aligned in the direction of X-ray source. In FIG. **28**, **2950** represents a small change in the angle with which the detector housings are constructed. In an embodiment, the construction angle is changed after every four detector housings. However, other configurations are employed in other embodiments.

Improved Material Discrimination

Material discrimination in the system of present specification is performed using a combination of two spectroscopic measurement techniques of the transmitted X-rays to improve the ability to determine the atomic number of the materials inside a container. The technologies considered are known as Z-determination by statistical count-rate analysis (Z-SCAN) and transmission Z-Spectroscopy (Z-SPEC). In an embodiment, conventional methods, such as dual-energy X-ray source technology, are used instead, or in addition.

Z-SPEC is a technique that determines individual X-ray energies arriving at the detector elements by producing a spectrum for each detector element. It is known in the art that the spectrum of X-rays changes when going through equivalent amounts of materials of different atomic number Z. FIG. **14** shows the spectra behind the equivalent of 8 inches of steel for lead **1501**, steel **1502**, and carbon **1503**, compared to the original bremsstrahlung spectrum **1504**. It is apparent from FIG. **14**, that the spectrum behind high-Z material has lower average energy, and is skewed towards lower energy. On the other hand, the spectrum behind low-Z material has higher average energy and is skewed towards higher energy. Z-SPEC measures the entire X-ray spectrum, and determines the Z of the material based on the shape of the spectrum, to determine the Z of the cargo material traversed. The Z-SPEC technique works best for a narrow (~10^2) attenuation dynamic range, and can be improved by using a high-duty-factor X-ray source.

Further details of implementation of the Z-SPEC technique are available in U.S. Pat. No. 8,750,454, entitled “High Energy Spectroscopy-Based Inspection Systems and Methods to Determine the Atomic Number of Materials”, which is incorporated herein by reference in its entirety.

Z-SCAN is a statistical technique which determines a feature called the Noise Figure Y of the energy spectrum of the X-rays arriving at the detector elements, through the use of fast detector materials and photo-detectors and wave-form digitization and analysis. This noise figure is a direct measure of the Z of the cargo material traversed.

In the Z-SCAN technique, the noise figure Y is defined as:

$$Y=\alpha\langle E^2\rangle/\langle E\rangle$$

where <E> is the mean X-ray energy and <E^2> is the mean of the square of the X-ray energies and α is a calibration constant. Since the signal in a given detector is:

$$S=\alpha\langle E\rangle N$$

and the mathematical variance of S is:

$$\delta S^2=\alpha^2\langle E^2\rangle N,$$

wherein N is the number of X-rays in a given signal S, δS is the standard deviation of statistical uncertainty in the measurement of signal S and δS^2 is the statistical variance.

The noise figure can thus also be written as:

$$Y=\delta S^2/S,$$

and can thus be determined from the data: the signal S is determined in the usual way, and the variance of S by measuring S many times and using the statistical relation for the standard deviation:

$$\delta S^2=\Sigma(S-\langle S\rangle)^2/(n-1)$$

where <S> is the average value of S and n is the number of measurements of S.

This is best done by measuring multiple samples of the signal for each pixel in the image, and then by combining multiple pixels belonging to the same object (found through a segmentation algorithm applied to the image).

The calculated noise figure is shown vs. transmission in FIG. **15** for a number of materials, such as Poly **1601**, Al **1602**, Fe **1603**, etc. at two different X-ray source energies of 9 MV and 6 MV.

Thus, Z-SCAN determines statistically the Z of the material. Further details of implementation of the Z-SCAN technique are available in U.S. Pat. No. 8,724,774, entitled “Method and System for Extracting Spectroscopic Information from Images and Waveforms”, which is incorporated herein by reference in its entirety.

X-ray spectroscopy (Z-SPEC) is a difficult process because the energy of individual X-rays needs to be measured in a very high count rate environment, since typical linear accelerator-based X-ray sources emit X-rays in large but short bursts. In an embodiment, the present specification describes a linear accelerator source with an increased duty factor to spread out the arrival of X rays at the detector array over time and hence provide improved material discrimination. In an embodiment, duty factor is enhanced to be in the range of 0.4-1.0% compared to 0.04-0.1% generally used in the commercially available X-ray systems. In an embodiment, the higher duty factor is achieved by moving from a typical 300 pulses per second to 1000 pulses per second and/or increasing the pulse duration from a typical 4 microseconds to 10 microseconds. While conventional X-ray sources use a magnetron, a high-duty-factor linac X-ray source requires the use of a klystron. It is known in the art that a klystron-based source uses more power. In order to limit klystron power consumption to a manageable amount, the linac beam centerline would need to be somewhat longer than those in current use, for a given electron beam energy. Since the X-ray beam spot has to be fairly low above the ground to enable vehicle scanning, and the X-ray fan beam ideally aims at an upward angle, it is not convenient to use a configuration where the electron beam is aimed straight at a target; as in that case the electron-gun end of the linac would be below ground level. Therefore, in an embodiment, the present specification employs a configuration where the X-ray source is mounted more or less vertically, and has a 245 degree turnaround magnet, aiming the X-ray beam at 25 degrees up towards the cargo.

This configuration is shown in more detail in FIG. **16**. Referring to FIG. **16**, linac **1701** is mounted vertically and is associated with klystron **1702**. The linac is equipped with the 245 degree magnet **1703**, which ensures that the radiation beam **1704** is aimed at the required angle. This configuration has the added advantage that the linac and its enclosure can be part of a single assembly together with the detector array, substantially reducing opportunities for the source and detector array to get out of alignment. One of ordinary skill in the art could appreciate that the above configuration of the X-ray source and the applied magnetic field is an exemplary configuration and there could be multiple other configurations to generate the resultant electron beam in a desired direction. In an embodiment, the present specification employs a configuration where the X-ray source is mounted at −25 degree angle and has a 270 degree magnet to generate an electron beam as illustrated in FIG. **16**. In another embodiment, the present specification employs a configuration where the X-ray source is mounted vertically and has a 270 degree magnet and an additional magnetic element to bend the electron beam by another 25 degrees to generate the same resultant electron beam as illustrated in FIG. **16**.

In an embodiment, if the instantaneous count rate of arriving signals is still too high, Z-SCAN is used in combination with Z-SPEC to provide improved material discrimination. In an embodiment, for cost and simplicity reasons, Z-SPEC, Z SCAN as well as radiographic imaging are combined into a single detector array.

In an embodiment, to provide high spatial resolution, fast and high-density detectors are used for Z-SPEC. In an embodiment, lead tungstate ($PbWO_4$) is used for manufacturing high density scintillation detectors. In an embodiment, since lead tungsten has low light output, fast photo detectors with some gain such as avalanche photodiodes or silicon photomultipliers are used in conjunction to overcome electronics noise. In another embodiment, high speed preamplifiers and digitizers are also used to ensure that the Z-SPEC process is conducted efficiently and signals don't pile up.

Material Categorization and Alarm Verification

In an embodiment, the system described in the present specification employs two levels of scanning to detect threats. In an embodiment, the present specification provides threat detection algorithm assist tools, and a software framework together with a user interface to implement the same. At the first level, in an embodiment, the X-ray image is displayed on an interface screen at the end of the primary scan. In an embodiment, suspicious locations are identified by ATR (Automatic Threat Recognition) algorithms during the X-ray scan. The operator can further use the tools provided in the software package to analyze the image and determine if the cargo is benign or suspicious. If the operator determines that certain suspect areas should be targeted for secondary screening, those areas can be tagged or marked using the image annotation tools provided in the software package. After all such areas have been marked, the inspector confirms the selections by clicking a scan decision button to prepare the inspection system for a secondary scan, if needed. At the end of the secondary scan, the X-ray image, along with the ATR results from both screenings, are displayed on the user interface. At the locations targeted for secondary screening, the results are highlighted to indicate them as benign or suspicious. The operator then makes a final decision on the cargo to either clear the container, or detain it for manual inspection.

In an embodiment, the present specification uses X-ray imaging for primary scanning and neutron-based interrogation to perform secondary screening. This allows the system to effectively determine the presence of bulk explosives, narcotics, chemical weapons and high-Z materials which might shield radioactive materials. The neutron subsystem is particularly useful for the detection of narcotics, specifically cocaine or heroin hydrochloride.

FIG. **17** illustrates the neutron subsystem, according to an embodiment of the present specification. Referring to FIG. **17**, in an embodiment, the neutron system comprises two 14 MeV neutron generators **1801** and **1802**, each located on a vertical side of the boom **1803**. The neutron generators are equipped with moderator/fan beam collimators (not shown). The system further comprises 15 NaI(Tl) detectors **1804** to provide the gamma-ray detection array, all located inside the boom.

One of ordinary skill in the art would appreciate that incorporation of the neutron system in the boom requires widening and strengthening the boom in order to accommodate the additional weight of the neutron system. This has the added benefit of making the boom less susceptible to boom sway, thereby reducing the "curtain artifact", and allowing the X-ray beam to be collimated more for reduced X-ray exclusion zone. Further, placing a neutron generator on each side of the boom allows detection of threats on both sides of the container with the operational efficiency of a single sided scan.

In an alternate embodiment, the neutron generator is placed on the horizontal boom on the top.

FIGS. **18***a* and **18***b* illustrate an X-ray scanning system along with the neutron scanning system in a front view **1900** as well as rear view **1910** of the boom **1920**, respectively. In one embodiment, the X-ray scanning system is the primary system. The neutron subsystem comprises the neutron sources **1901** and the NaI detectors **1902** to detect material-specific gamma rays that may be emitted from materials in the cargo irradiated by the neutrons. The X-ray sub-system comprises the X-ray source (not shown) and detector array boards **1903**. Each detector assembly board is also inserted into a steel collimator **1904**, as described earlier with reference to FIG. **13**. The system also comprises a lead back stop **1905** located behind the detector arrays on the vertical side of the boom, and an external collimator **1906** located on the opposite side. The external collimator **1906** is built into the proximal vertical boom, and has a wedge-shaped profile, i.e. it is wider on the source side to allow all X rays to enter the collimator, and narrower on the detector side in order to allow only collimated X rays to exit.

FIG. **19** shows further details of the detector arrays **2001** in the vertical side of the boom **2002**. A V-shaped channel **2003** is provided in the lead back stop **2004**, which prevents X-rays from scattering sideways.

In an embodiment, the neutron system uses a wide (in the vertical plane) fan beam. This has the advantage that the threat does not need to be localized vertically, and the system does not need to have the same view of the cargo as the X-ray system, as would be required using a collimated neutron source.

In an embodiment of the present specification the shielding design of the neutron generator is developed after a complex optimization between overall weight, signal strength and cost. The function of the shielding is three-fold: first, the shielding moderates the fast neutrons and produces thermal neutrons for inspection; second, it acts as a radiation shield where it attenuates the fast neutrons and keeps them from interacting within the detectors; and thirdly, it also minimizes radiation dose to the operators and the general public.

In an embodiment, each neutron generator produces 14.1 MeV neutrons that are isotropically emitted from the target location within the generator. All shielding designs considered are of a layered design composed of different materials. The layered geometry allows materials to be chosen for their specific neutron-energy-dependent attenuation, in light of the fact that the average neutron energy falls off as the neutrons penetrate the shield.

The general strategy for the neutron shielding design is to use materials that "reflect" neutrons, in order to redirect neutrons that would otherwise exit and cause background. Some materials also tend to moderate the neutron energy through the (n, 2n) reaction by ejecting a second neutron when hit by an energetic neutron. Common materials with a low (n, 2n) reaction threshold are tungsten and lead. Another material that moderates neutrons through the (n, 2n) reaction, as well as elastic scattering, is beryllium. Hydrogen-containing materials such as polyethylene (CH_2) moderate neutrons from elastic scattering of the neutrons off of hydrogen atom.

FIG. **20** illustrates a three-layered shielding collimator design. Referring to FIG. **20**, the three-layer spherical moderator design comprises layers of lead **2101**, beryllium **2102** and polyethylene **2103**. The layer of lead **2101** immediately surrounding the neutron generator acts to reflect and attenuate the 14.1 MeV neutrons. The polyethylene sphere **2102** generates a high thermal neutron flux for signal production. It also provides good radiation dose suppression which minimizes the exclusion zone surrounding the system. The beryllium layer **2103** is efficient in reducing the neutron energy through elastic scattering as well as through the (n, 2n) reaction. The advantage of utilizing beryllium over polyethylene is that beryllium does not have a high thermal neutron capture cross-section. This allows the low-energy neutrons to survive the attenuation and traverse into the cargo container.

The present moderator design optimizes the narcotics signal while minimizing the radiation exposure and system weight.

To further reduce the radiation footprint generated by the 14.1 MeV source neutrons, the present system, in an embodiment, employs direction-specific shielding. In an embodiment, an additional polyethylene shielding is placed around the three-layer moderator, as shown in FIG. **21**. Referring to FIG. **21**, the shielding **2201** is designed to block those neutrons emitted at specific angles that contribute to the radiation dose at large distance (>25 feet). The specificity of the shielding geometry allows a maximum shielding effect with minimal additional weight.

In an embodiment, directional shielding ring **2201** blocks fast neutrons from 4° above the neutron source horizontal plane to 17.5° below the horizontal plane. In an embodiment, 40% reduction in dose can be achieved in the exclusion zone as well as at the operator location with this directional shield placed around both neutron generator collimators. Clearly, other designs are possible that optimize utility and spatial considerations.

The primary benefit of the secondary inspection is to avoid performing devanning of the vehicle under inspection to check for possible threats. Presumably, in the case where a threat object is considered highly suspicious, devanning would automatically be indicated, but for a wide range of somewhat suspect areas in an X-ray image, a direct scan using neutrons would quickly provide additional information.

The above examples are merely illustrative of the many applications of the system of present invention. Although only a few embodiments of the present invention have been described herein, it should be understood that the present invention might be embodied in many other specific forms without departing from the spirit or scope of the invention. Therefore, the present examples and embodiments are to be considered as illustrative and not restrictive, and the invention may be modified within the scope of the appended claims.

We claim:

1. An X-ray source for scanning an object comprising:

an electron beam generator, wherein said electron beam generator generates an electron beam;

an accelerator for accelerating said electron beam in a first direction; and,

a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements, wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that the target substantially only generates X-rays focused toward a high density area in the scanned object.

2. The X-ray source of claim **1**, wherein said high density section in the scanned object is estimated in a second pulse using image data captured by a detector array in a first pulse and wherein the direction of the electron beam is optimized by said X-ray source during said second pulse to focus X-rays towards said high density area in the scanned object based on said image data in said first pulse.

3. The X-ray source of claim **2**, wherein the intensity of the electron beam is optimized in each pulse to ensure that targeted areas in the scanned object are irradiated with an optimal dose of X-rays.

4. The X-ray source of claim **1**, wherein said magnetic field causes said electron beam to strike the target at the same point but at a different angle in each successive pulse such that the angle at which said electron beam strikes the target depends on the position of the high density area in the scanned object.

5. The X-ray source of claim **1**, wherein said magnetic field causes said electron beam to strike the target at the same point from different directions in successive pulses.

6. The X-ray source of claim **1**, wherein said electron beam comprises single energy radiation.

7. The X-ray source of claim **6**, wherein said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise a quadrupole magnet.

8. The X-ray source of claim **1**, wherein said electron beam comprises dual energy radiation.

9. The X-ray source of claim **8**, wherein said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise a pulsed quadrupole magnet.

10. The X-ray source of claim **8**, wherein said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise two quadrupole magnets, wherein each quadrupole magnet is configured to transport at least one of the radiation energies in the dual energy radiation beam.

11. The X-ray source of claim **1**, wherein said target is manufactured from a material having low atomic number.

12. The X-ray source of claim **11** wherein said target is manufactured from carbon, graphite or diamond.

13. The X-ray source of claim **1**, wherein said target is shaped.

14. The X-ray source of claim **13** wherein said target is of a semi-circular, triangular, or flat shape.

15. The X-ray source of claim **1**, further comprising shielding optimized to reduce the system weight.

16. The X-ray source of claim **1**, wherein said linear accelerator is mounted in a substantially vertical direction.

17. An inspection system for scanning cargo or vehicles comprising:

an X-ray source for generating an electron beam;

an accelerator for accelerating said electron beam in at least one predefined direction;

a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements, wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that it substantially only generates X-rays focused toward a specific high density area in the scanned object; and,

an X-ray detector array for detecting the radiation transmitted through the object under inspection.

18. The system of claim **17**, wherein said inspection system is mounted on a mobile inspection vehicle.

19. The system of claim **17**, wherein said high density area in the scanned object is estimated in a second pulse using image data captured by the detector array in a first pulse and wherein the direction of electron beam is optimized by said X-ray source during said second pulse to focus X-rays towards said high density area in the scanned object based on said image data in said first pulse.

20. The system of claim **17**, wherein the intensity of electron beam is optimized for each pulse to ensure that targeted areas in the scanned object are radiated with an optimal dose of X-rays.

21. The system of claim **17**, wherein said magnetic field causes said electron beam to strike the target at the same point but at a different angle in each successive pulse such that the angle at which said electron beam strikes the target depends on the position of high density area in the scanned object.

22. The system of claim **17**, wherein said magnetic field causes said electron beam to strike the target at different points in successive pulses.

23. The system of claim **17**, wherein said electron beam comprises single energy radiation.

24. The system of claim **23**, wherein said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise a quadrupole magnet.

25. The system of claim **17**, wherein said electron beam comprises dual energy radiation.

26. The system of claim **25**, wherein said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise a pulsed quadrupole magnet.

27. The system of claim **25**, wherein said first set of magnetic elements comprise a pulsed dipole magnet and said second set of magnetic elements comprise two quadrupole magnets wherein each quadrupole magnet is configured for transporting at least one of the radiation energies in the dual energy radiation beam.

28. The system of claim **17**, wherein said target is manufactured from a material having low atomic number.

29. The system of claim **18** wherein said target is manufactured from carbon, graphite, or diamond.

30. The system of claim **17**, wherein said target is shaped.

31. The system of claim **30**, wherein said target is of a semi-circular, triangular, or flat shape.

32. The system of claim **17**, further comprising a shielding optimized to reduce the system weight.

33. The system of claim **17**, wherein said X-ray source is a linear accelerator mounted in a substantially vertical direction.

34. The system of claim **17**, wherein said system further conducts transmission Z-spectroscopy to analyze at least one material contained in the scanned object.

35. The system of claim **17**, wherein said system further conducts noise spectroscopy to analyze at least one material contained in the scanned object.

36. The system of claim **17**, further comprising at least one X-ray filter for vertically modulating x-ray intensity.

37. The system of claim **17**, wherein said X-ray detector array comprises one or more gapless X-ray detector arrays to detect the radiation transmitted by the scanned objects.

38. The system of claim **37**, wherein said gapless detector array comprises a two-dimensional array of small detector elements and wherein each detector element comprises a scintillator.

39. The system of claim **17**, further comprising a neutron-based inspection subsystem comprising a pair of neutron generators and a plurality of gamma-ray detectors.

40. An X-ray source for scanning an object comprising:

an electron beam generator, wherein said electron beam generator generates an electron beam;

an accelerator for accelerating said electron beam in a first direction; and,

a first set of magnetic elements for transporting said electron beam into a magnetic field created by a second set of magnetic elements, wherein the magnetic field created by said second set of magnetic elements causes said electron beam to strike a target such that the target generates X-rays, wherein a majority of the X-rays are focused on a high density area in the scanned object and a minority of the X-rays are focused elsewhere.

41. An X-ray source for scanning an object comprising:

an accelerator capable of generating a sequence of pulsed electron beams of two or more different energies moving in a pre-defined direction, wherein a first pulse is low energy, a second pulse is high energy and each subsequent pulse in the sequence alternates between low energy and high energy; and,

a set of electron steering components which causes the beam to strike the same area of the target at pre-defined angles, wherein said angle is estimated from at least one image captured from any previous pulse in the sequence of pulses of said electron beam.

42. The X-ray source of claim **41** wherein the steering components include a pulsed steering magnet and a pulsed quadrupole.

43. The X-ray source of claim **41** wherein the steering components include a pulsed steering magnet and at least two DC magnets.

44. The X-ray source of claim **41** wherein the low energy beam ranges from 4 MeV to 6 MeV and the high energy beam ranges from 6 MeV to 10 MeV.

45. The X-ray source of claim **41** wherein the target is fabricated from tungsten, a low-z material such as graphite, or copper depending upon the application.

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